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DEVELOPMENT OF A HIGH-STRENGTH, STRESS-CORROSION-RESISTANT ALUMINUM ALLOY FOR USE IN THICK SECTIONS

M. V. Hyatt and H. W. Schimmelbusch

The Boeing Company

TECHNICAL REPORT AFML-TR-70-109

May 1970

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DEVELOPMENT OF A HIGH-STRENGTH, STRESS-CORROSION-RESISTANT ALUMINUM ALLOY FOR USE IN THICK SECTIONS

M. V. Hyatt and H. W. Schimmelbusch

FOREWORD

This report was prepared by the Structures Technology-Materials section, Commercial Airplane Group, The Boeing Company, Seattle, Washington. The research was supported jointly by the ARPA Coupling Program on Stress-Corrosion Cracking (ARPA Order No. 878) and Contract No. AF33(615)-3697, Supplemental Agreement No. 3, entitled "Development of High-Strength Aluminum Alloys with Improved Stress Corrosion Resistance."

Air Force funds provided for casting and partial fabrication of the experimental alloy. Remaining fabrication and all testing and characterization work were funded by the Advanced Research Projects Agency (ARPA) contract. The Air Force portion of the program was administered by the Air Force Materials Laboratory, Air Force Systems Command, United States Air Force, with Dr. T. M. F. Ronald, MAMP, as project engineer. Dr. D. E. Piper is project director of the Boeing component of the ARPA contract. This report covers the period July 1, 1968, through March 15, 1970. The manuscript was released by the authors in March 1970 for publication as a technical report.

The authors acknowledge the assistance of the Materials Technology Laboratories during the course of this program. From the Structures Technology-Materials staff, D. N. Farwick and F. K. Downey provided test support, D. N. Farwick and R. J. LaPorte were responsible for optical metallography, D. D. Early performed the transmission electron microscopy, and A. L. Wingert and R. H. Olsen performed the microprobe analysis. The authors are grateful to D. O. Sprowls of the Alcoa Research Laboratories for supplying the engineering drawings used in fabricating the stressing frames and stressing jig used for a portion of the stress-corrosion work in this contract.

This report has been given The Boeing Company document number D6-60122. This technical report has been reviewed and is approved.

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ABSTRACT

Several heats of a Boeing-recommended alloy (alloy 21) were cast by Reynolds and fabricated by Reynolds and Wyman-Gordon into die forgings, hand forgings, plate, and extrusions. All the wrought products were forwarded to Boeing for heat treatment and evaluation of mechanical, fracture, fatigue, and stress-corrosion properties.

Heat-treatment studies were performed on specimens of from 3-in.-thick plate of the new alloy. The degree of overaging required to achieve a 25-ksi smooth-specimen threshold stress was determined using stress-corrosion crack growth rate data from precracked double cantilever beam specimens. Based on these data, a T6 + 35 hr at 325°F treatment was finally selected. Metallographic studies on failed and unfailed smooth stress-corrosion specimens verified that the selected heat treatment was adequate to meet the stress-corrosion goal.

The wrought products of alloy 21 were heat treated in Boeing production facilities according to the heat treatment selected. Mechanical, fracture, and stress-corrosion properties for die forgings of alloy 21 and several other forging alloys may be seen in the following table.

Alloy	Thickness (in.)	Minimum longitudinal properties F_{tu} (ksi)	Minimum longitudinal properties 0.2% F_{ty} (ksi)	Longitudinal K_{Ic} range (ksi$\sqrt{in.}$)	Short-transverse stress-corrosion threshold (ksi): 3.5% NaCl alternate immersion	Short-transverse stress-corrosion threshold (ksi): Industrial atmosphere
Alloy 21	6.75	69*	60*	30–38*	>25*	>25*
7049-T73	5.0	70	60	30–38*	45	?
X7080-T7	6.0	65	57	27–30	25	15
7075-T73	3.0	66	56	27–38	>47	>47
7075-T73	6.0	61	51	27–38	>47	>47
7175-T736	3.0 max	76	66	27–38	~35	?
7075-T6	3.0 max	75	65	25–32	7	14
7079-T6	6.0	72	62	25–32	7	6

* Estimated values

The mechanical properties of alloy 21 are comparable to those of 7049-T73. The fracture toughness of alloy 21 is as good as or better than that of the other alloys listed. The smooth-specimen short-transverse stress-corrosion threshold appears to be greater than 25 ksi. Test data also indicate that the smooth and notched axial (tension-tension) fatigue properties of alloy 21 are comparable to those of 7075-T6 and 7075-T73.

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NOMENCLATURE

a	crack length measured from load point (centerline of loading bolt) (in.)
a_o	an empirical rotation correction equal to 0.6h
a_f	final crack length measured from load point (in.)
b	specimen thickness
B	thickness of bend specimen
C	center location
c	specimen compliance (reciprocal stiffness) when the crack length is a
da/dt	crack growth rate (in./hr or Å/sec)
DCB	double cantilever beam
E	modulus of elasticity (10.3×10^6 for aluminum alloys)
E/D	edge margin to hole diameter ratio
F_{tu}	tensile ultimate strength (psi, ksi)
F_{ty}	tensile yield strength (psi, ksi)
G	crack extension force or strain energy release rate
h	½ specimen height
I	moment of inertia of one of the arms of the DCB specimen ($in.^4$)
IACS	International Annealed Copper Standard
K	stress intensity factor (ksi$\sqrt{in.}$)
K_I	plane-strain stress intensity factor, opening mode of crack extension (ksi$\sqrt{in.}$)
K_{Ic}	plane-strain fracture toughness at onset of unstable crack growth (ksi$\sqrt{in.}$)
K_{Iscc}	plane-strain stress intensity below which SCC will not occur
K_t	theoretical stress concentration factor
L	longitudinal grain direction or specimen length (in.)
LT	long-transverse grain direction
M	applied bending moment (in.-lb)
P	load (lb)
R	ratio of minimum cyclic stress to maximum cyclic stress
RA	reduction in area (percent)
R_B	Rockwell B hardness
RMS	root mean square
r	radius
S	surface location or support span for notched bend specimen (in.)
SCC	stress-corrosion cracking
ST	short-transverse grain direction
T	transverse grain direction
v	total deflection of the two arms of a double cantilever beam specimen at the load point (in.)
W	specimen depth for the notched bend specimen (in.)

NOMENCLATURE (CONTINUED)

w	panel width (in.)
σ_g	gross area stress at fracture (ksi)
σ_{ys}	yield strength (ksi)

SECTION I

INTRODUCTION

The majority of in-service stress-corrosion problems in today's high-performance structures occur in 7000 series alloys such as 7075-T6, 7178-T6, and particularly 7079-T6. Although the overaged alloy 7075-T73 offers significant stress-corrosion resistance, use of this alloy can result in weight penalties because of its lower strength, particularly in thick-section applications. The recently introduced 7175-T736 alloy can offer good stress-corrosion resistance and exceptionally high strengths, but this alloy is not available for thick-section applications.

The 7075-type alloys in thick sections have low strength because these Al-Zn-Mg-Cu-Cr alloys are highly quench sensitive. Thus, strength properties drop off rapidly with decreasing quench rate (or increasing thickness). Quench sensitivity can be reduced by minimizing the concentration of the recrystallization retardant, chromium, or by replacing chromium with other recrystallization retardants such as manganese and zirconium, which have less effect on quench sensitivity (1,2,3,4). Reductions in copper content decrease quench sensitivity (2,5), but may also decrease stress-corrosion resistance. Reductions in magnesium and zinc content decrease quench sensitivity (2), but also lower strength properties.

One recent alloy, X7080-T7, was developed to provide stress-corrosion resistance and good thick-section mechanical properties. This alloy, by virtue of low copper content and replacement of chromium with manganese, maintained attractive mechanical properties in thick sections even though it was boiling water quenchable. The boiling water quench was particularly useful in minimizing residual quenching stresses and subsequent distortion during machining. This alloy also showed adequate stress-corrosion resistance when tested by 3.5% NaCl alternate immersion, having a short-transverse threshold stress of 25 ksi. Subsequent testing in outdoor industrial environments, however, showed that stress-corrosion failures in short-transverse specimens occurred at stresses as low as 15 ksi (6). Since those results were published, less interest has been shown in X7080-T7 for thick-section forging applications.

Work aimed at developing a high-strength, thick-section alloy with adequate stress-corrosion resistance has continued at Alcoa, Reynolds, Kaiser, and Boeing.

The Boeing program reported here is based on an alloy composition recommended as the result of previous contract work on the effects of silver, boron, cerium, yttrium, and zirconium (5,7) on stress-corrosion resistance. The nominal composition of the recommended alloy (designated alloy 21) is shown in Table 1. The nominal composition and composition range for alloy 21 are plotted in Fig. 1. Alloy 21 is essentially a 7075-7178-type alloy that contains low copper and in which zirconium and manganese replace chromium. Several ingots of this alloy were cast by Reynolds Metals Company and were fabricated into hand and die forgings, extrusions, and plate by Reynolds and Wyman-Gordon. The material was sent to Boeing for heat treatment and evaluation. The stated contract objective for this alloy was: ". . .a minimum tensile yield stress of 70,000 psi, a minimum short transverse,

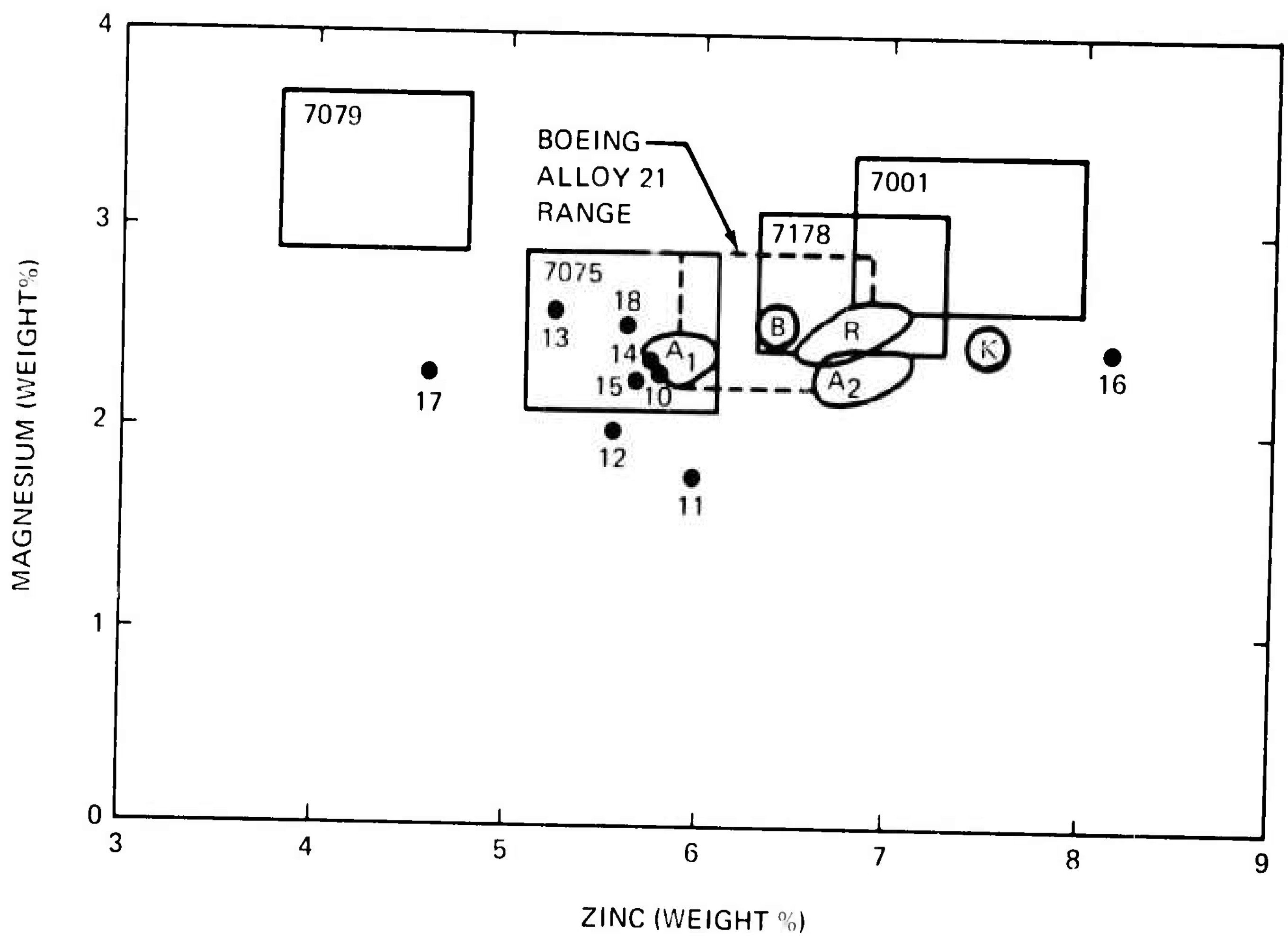
Table 1. Chemical Compositions of Thick-Section Experimental and Commercial Alloys

Alloy	Zn	Mg	Cu	Fe	Si	Ti	Be	Mn	Cr	Zr	Ni	V	Reference
Boeing Alloy 21	6.40	2.55	1.10	0.13	0.06	0.02	0.001	0.10	<0.01	0.13	<0.01	—	5
Reynolds Alloys													
1	6.87	2.56	1.22	0.07	0.05	0.04	0.002	< 0.01	< 0.01	0.08	—	—	
2	6.58	2.39	1.22	0.07	0.05	0.03	0.002	< 0.01	< 0.01	0.11	—	—	
3	6.72	2.46	1.18	0.06	0.03	0.05	0.002	< 0.01	< 0.01	0.18	—	—	
4	6.66	2.42	1.20	0.07	0.04	0.03	0.004	< 0.01	0.04	<0.01	—	—	
5	6.97	2.60	1.39	0.06	0.05	0.03	0.002	< 0.01	0.11	<0.01	—	—	
6	6.54	2.41	1.23	0.07	0.04	0.02	0.001	0.10	< 0.01	<0.01	—	—	
7	6.87	2.60	1.21	0.08	0.04	0.03	0.001	0.26	< 0.01	<0.01	—	—	
8	6.76	2.61	1.22	0.08	0.04	0.02	0.001	0.39	< 0.01	<0.01	—	—	
9	6.62	2.35	1.21	0.08	0.04	0.03	0.002	0.35	0.05	0.06	—	—	9
10	6.85	2.41	1.15	0.08	0.04	0.03	0.001	0.31	0.05	0.13	—	—	
11	6.90	2.42	1.19	0.07	0.04	0.04	0.002	< 0.01	0.04	0.08	—	—	
12	6.51	2.38	1.17	0.08	0.03	0.06	0.002	< 0.01	0.05	0.13	—	—	
13	6.78	2.63	1.23	0.08	0.05	0.04	0.002	0.30	< 0.01	0.11	—	—	
14	6.57	2.41	1.18	0.08	0.03	0.05	0.001	0.51	0.10	0.16	—	—	
15	6.64	2.38	1.20	0.06	0.05	0.03	<0.001	< 0.01	< 0.01	< 0.01	—	—	
16	7.11	2.61	1.39	0.06	0.04	0.03	<0.001	< 0.01	0.12	< 0.01	—	—	
Alcoa Alloys													
A	5.90	2.20	2.40	—	—	—	—	0.34	0.01	—	—	—	11
NAVAIR 3	5.69	2.39	2.36	0.09	0.08	0.02	—	0.28	0.00	0.00	—	—	
NAVAIR 4	5.95	2.46	2.44	0.10	0.03	0.03	—	0.01	0.00	0.11	—	—	
NAVAIR 5	6.86	2.17	2.32	0.12	0.05	0.07	—	0.33	0.00	0.00	—	—	
NAVAIR 6	6.64	2.13	2.45	0.09	0.07	0.03	—	0.01	0.00	0.10	—	—	
NAVAIR 7	6.67	2.37	2.27	0.09	0.05	0.02	—	0.16	0.00	0.10	—	—	13
NAVAIR 8	6.63	2.33	2.35	0.09	0.05	0.03	—	0.15	0.06	0.00	—	—	
NAVAIR 9	7.06	2.25	2.12	0.12	0.05	0.07	—	0.33	0.00	0.00	—	—	
NAVAIR 10	7.10	2.40	2.33	0.07	0.04	0.03	—	0.01	0.00	0.11	—	—	

Table 1. -- Concluded

Alloy	Zn	Mg	Cu	Fe	Si	Ti	Be	Mn	Cr	Zr	Ni	V	Reference
1	6.04	2.30	2.31	0.07	0.05	0.01	0.000	0.00	0.00	0.00	0.00	0.12	
2	6.01	2.35	2.39	0.08	0.05	0.02	0.000	0.00	0.04	0.00	0.00	0.12	
3	6.09	2.42	2.42	0.09	0.06	0.04	0.000	0.13	0.00	0.00	0.00	0.12	
4	5.80	2.46	2.22	0.09	0.05	0.04	0.000	0.00	0.00	0.12	0.00	0.15	
5	5.82	2.32	2.21	0.09	0.04	0.03	0.000	0.00	0.05	0.13	0.00	0.00	14
6	5.86	2.38	2.15	0.24	0.05	0.04	0.000	0.00	0.00	0.01	0.28	0.01	
7	5.78	2.28	2.46	0.10	0.05	0.03	0.000	0.00	0.00	0.13	0.00	0.15	
9 (NAVAIR 4)	5.96	2.30	2.37	0.08	0.04	0.03	0.000	0.03	0.00	0.12	0.00	0.00	
10	5.77	2.30	1.94	0.08	0.05	—	—	—	—	0.11	—	—	
11	5.95	1.75	2.31	0.09	0.05	—	—	—	—	0.12	—	—	
12	5.54	1.99	1.95	0.06	0.04	—	—	—	—	0.11	—	—	
13	5.24	2.59	2.54	0.07	0.04	—	—	—	—	0.12	—	—	
14	5.76	2.32	2.96	0.09	0.04	—	—	—	—	0.11	—	—	14
15	5.67	2.25	2.27	0.20	0.06	—	—	—	—	0.10	—	—	
16	8.10	2.41	1.72	0.06	0.04	—	—	—	—	0.13	—	—	
17	4.60	2.26	2.42	0.07	0.04	—	—	—	—	0.11	—	—	
18	5.61	2.52	2.24	0.08	0.05	—	—	0.17	—	0.11	—	—	
X7080	5.88	2.29	0.90	0.13	0.08	<0.02	—	0.32	0.01	—	—	—	18
Kaiser Alloy 7049	7.50	2.45	1.48	0.13	0.07	<0.10	—	0.01	0.16	—	—	—	19

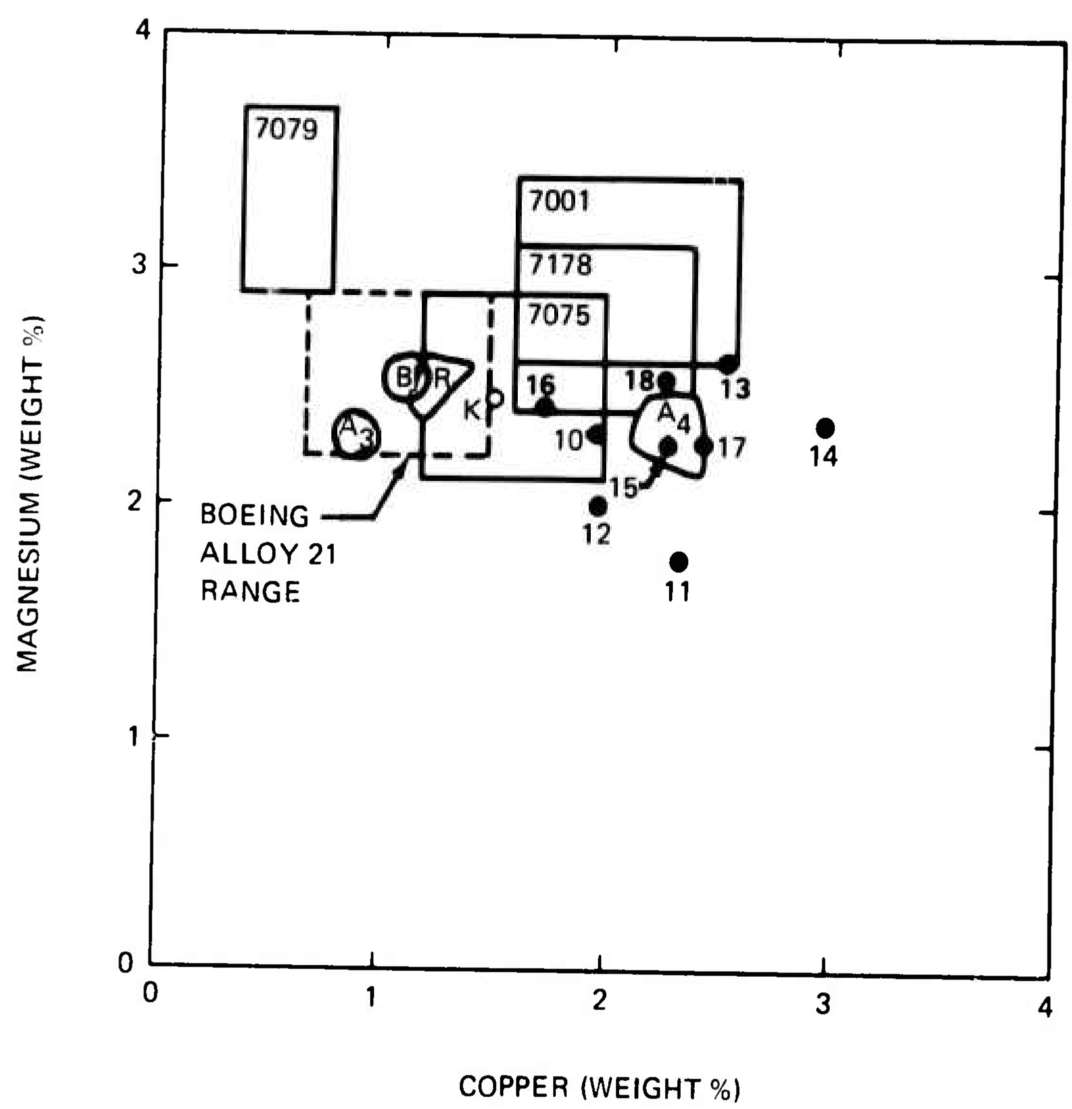
— indicates that the element was present in only minor amounts and was not quantitatively measured



SYMBOL	SOURCE	ALLOY	ADDITIONS
B	BOEING	21	Zr, Mn
R	REYNOLDS	1-16	Zr, Mn, Cr
K	KAISER	7049	Cr
		X7080	Mn
A_1	ALCOA	ALLOY A	Mn
		NAVAIR 3, 4	Zr, Mn
		1-9	Zr, Mn, Cr, V, Ni
A_2	ALCOA	NAVAIR 5-10	Zr, Mn, Cr
●	ALCOA	10-18	Zr, Mn

A. Magnesium-Zinc Plot

Figure 1. Chemical Compositions of Thick-Section Experimental and Commercial Alloys in Relation to 7079, 7075, 7178, and 7001



SYMBOL	SOURCE	ALLOY	ADDITIONS
B	BOEING	21	Zr, Mn
R	REYNOLDS	1-16	Zr, Mn, Cr
K	KAISER	7049	Cr
A_3	ALCOA	X7080	Mn
A_4	ALCOA	ALLOY A	Mn
		NAVAIR 3-10	Zr, Mn, Cr
		1-9	Zr, Mn, Cr, V, Ni
●	ALCOA	10-18	Zr, Mn

B. Magnesium-Copper Plot

Figure 1.–Continued

stress-corrosion threshold stress of 25,000 psi, good toughness and fatigue properties, and a quench sensitivity such that the properties can be maintained in thick plate and forgings."

Although minimum property goals for thick sections have been lowered in the more recent Alcoa and Reynolds contracts (8,9), these contracts are nevertheless aimed at the same goal as the Boeing program. The stated objective for the Alcoa and Reynolds programs is: ". . .the development of a high-strength, general purpose forging aluminum alloy. The alloy shall be capable of production using presently available commercial processes and heat treatments, and it shall have the following properties (minimum values, not typical values):

1. A minimum longitudinal 0.2% yield stress of 72,000 psi in 3-in. thick plate.
2. A minimum longitudinal 0.2% yield stress of 63,000 psi in 8-in. thick forgings.
3. A minimum short transverse stress-corrosion threshold stress of 25,000 psi (as measured in alternate immersion salt solution tests).
4. A minimum toughness, K_{Ic}, of 35,000 psi $\sqrt{\text{in.}}$
5. A minimum fatigue strength equal to that of 7075-T6."

The Reynolds approach is to utilize a base composition very similar to the Boeing alloy but with just slightly higher zinc content and lower iron and silicon contents (Table 1 and Fig. 1). Manganese, zirconium, and chromium additions are being studied by Reynolds (9,10).

Alcoa is investigating a much broader range of zinc and magnesium contents, and most of the Alcoa alloys contain medium to high copper (Table 1 and Fig. 1). Vanadium, zirconium, manganese, nickel, and chromium additions are being studied by Alcoa (8,11,12,13,14, 15).

Kaiser (16) has recently introduced another candidate for the thick-section alloy market designated 7049-T73 (Table 1 and Fig. 1). This alloy has high zinc content, medium copper content, and chromium additions.

The current Boeing program on alloy 21 was divided into three phases. In Phase I the effects of quench rate and room-temperature delay time before artificial aging were investigated to select a room-temperature delay time for use in subsequent work. In Phase II the effect of quench rate and degree of overaging on mechanical properties and stress-corrosion resistance were studied to select the final heat treatment for hand and die forgings, extrusions, and plate. All wrought products were then heat treated in Boeing production facilities using the selected heat treatment. In Phase III the mechanical, fracture, fatigue, and stress-corrosion properties of the alloy were determined.

Because of the similar objectives of the Boeing, Reynolds, and Alcoa contracts, available information on all these programs is presented in this report. In addition, some comparisons are made with data reported by Alcoa under Contract N00019-68-C-0146 (6). This contract was also aimed at the development of high-strength, stress-corrosion-resistant aluminum alloys. Data for X7080-T7 (17,18), 7049-T73 (16,19), and 7175-T736 (20,21) are also compared. Based on these data, some perspective on the mechanical properties of the various contract and commercial alloys can be achieved. Complete comparison of the relative stress-corrosion resistance of the Boeing, Alcoa, and Reynolds contract alloys must await further testing.

SECTION II

EXPERIMENTAL MATERIALS

1. CASTING

All plate, forging, and extrusion ingots of alloy 21 were cast in the experimental foundry, Metallurgical Research Division, Reynolds Metal Company, Richmond, Virginia. The Reynolds patented Controlled Cooling casting process, used at their Massena plant to cast forging quality ingots, was employed.

The metal was melted in a 2,000-lb-capacity, gas-fired, open-hearth furnace. All melts were chlorine fluxed for approximately 1 hr until the Straube-Pfeiffer vacuum gas sample showed no bubbles. The molten metal was laundered to the casting station through a preheated alumina ball filter to remove nonmetallic inclusions. A final chemical analysis button was taken halfway through each cast. The ingot analyses are shown in Table 2.

After casting, the ingots were stress relieved at 650°F for 16 hr and subsequently homogenized for 24 hr at 870° to 880°F. Each ingot was checked ultrasonically for cracks or other defects. Metallographic studies of the ingots showed them to be of sound quality, with a uniform cast grain size of about 0.002 to 0.003 in. Some porosity and zirconium-bearing intermetallics were present (Fig. 2).

2. FABRICATION

Two 14-in.-diam ingots (one 28 in. long and the other 45 in. long) and three 6-in.-diam, 60-in. long ingots were shipped to Reynolds's Phoenix extrusion plant for processing according to the standard practice for 7178. Prior to extrusion, the ingots were scalped and soaked 48 hr at solution temperature. Figure 3 shows the extruded products produced.

Two 14-in.-diam, 60-in.-long forging ingots were scalped to 13 in. and then sent to Wyman-Gordon, Worcester, Massachusetts, for die and hand forging fabrication. Figures 4 and 5 show the landing gear and Navajo die forging configurations, respectively. Figure 6 is a schematic representation of the hand forging configurations produced. Details of Wyman-Gordon's processing of the die and hand forgings are listed in Table 22, Appendix I.

Two 8-in. by 24-in. by 60-in. plate ingots were scalped to 7-in. thickness and sent to Reynolds's McCook plant for rolling according to standard rolling practice for 7178. Figure 7 illustrates the plate products produced.

All final fabricated materials, including an extra 13-in.-diam, 19-in.-long scalped ingot were shipped to Boeing for evaluation.

Table 2. Compositions of Alloy 21 Ingots [a,b]

Ingot size (in.)	Number of ingots	Zn	Mg	Cu	Fe	Si	Ti	Be	Mn	Cr	Zr	Ni
6 Dia (for extrusions)	4	6.28	2.40	1.09	0.13	0.06	0.01	0.001	0.12	<0.01	0.13	<0.01
14 Dia (for forgings)	2	6.36	2.55	1.06	0.13	0.07	<0.01	0.002	0.10	<0.01	0.18	0.01
		6.51	2.36	1.07	0.14	0.07	0.02	0.002	0.11	<0.01	0.14	0.01
14 Dia (for extrusions)	2	6.40	2.50	1.12	0.13	0.06	0.02	0.002	0.10	<0.01	0.11	<0.01
		6.39	2.44	1.17	0.14	0.07	0.02	0.002	0.10	<0.01	0.10	<0.01
8 x 24 (for plate)	2	6.21	2.52	1.13	0.15	0.07	0.02	0.001	0.10	<0.01	0.12	<0.01
		6.27	2.48	1.06	0.13	0.06	0.02	0.002	0.10	<0.01	0.13	<0.01
[a]Composition Range for Alloy 21		5.9-6.9	2.2-2.9	0.7-1.5	0.20 max	0.20 max	0.10 max	—	0.05-0.15	0.05 max	0.10-0.25	—

[b]Weight percent

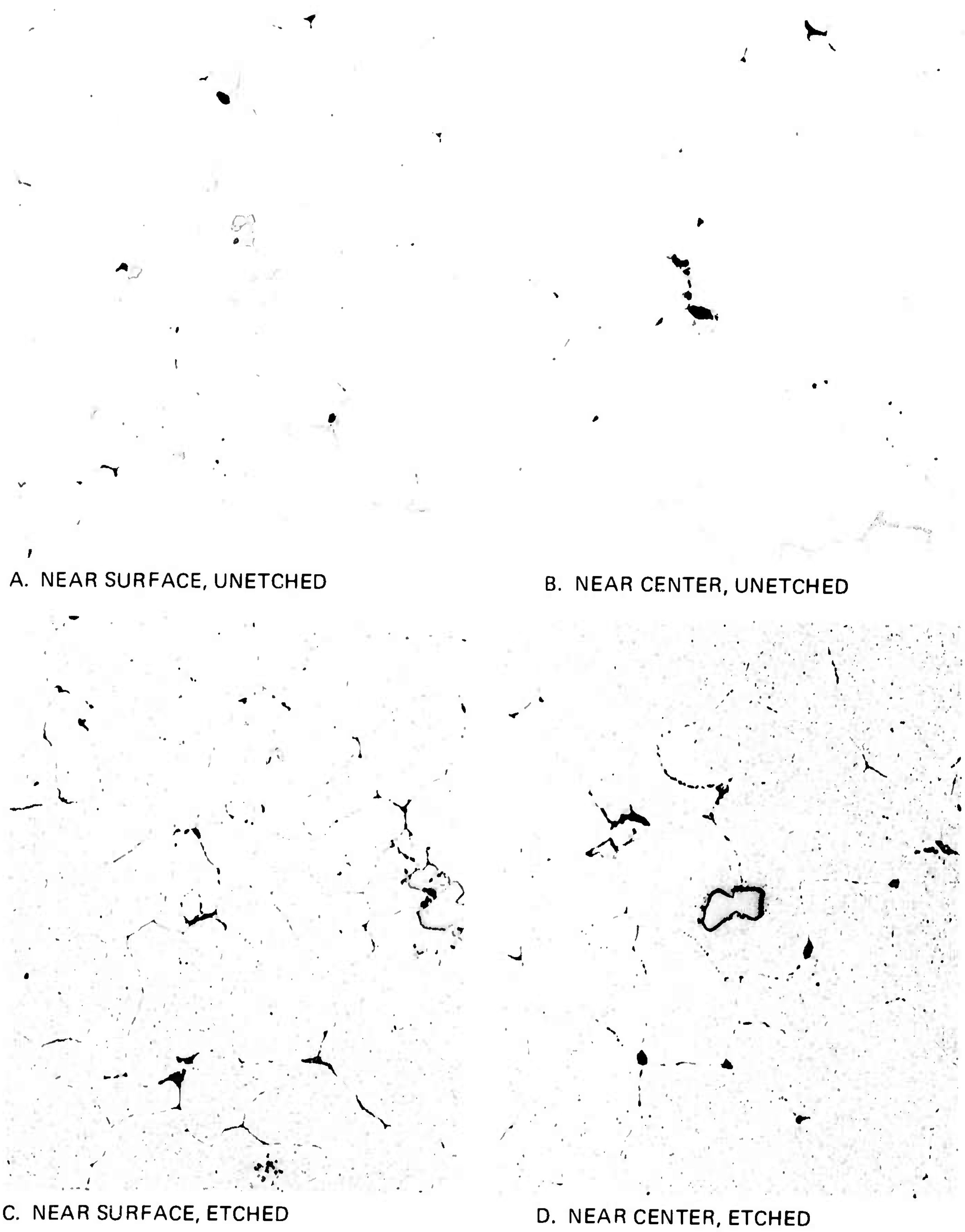


Figure 2. Microstructure Near Surface and Center of 14-Inch-Diameter Homogenized and Annealed Ingot of Alloy 21 (200X). Note Porosity in A and B and the Large, Gray, Zirconium-Bearing Intermetallic Particles in C and D. There Is Little Difference in Grain Size from Surface to Center of the Ingot.

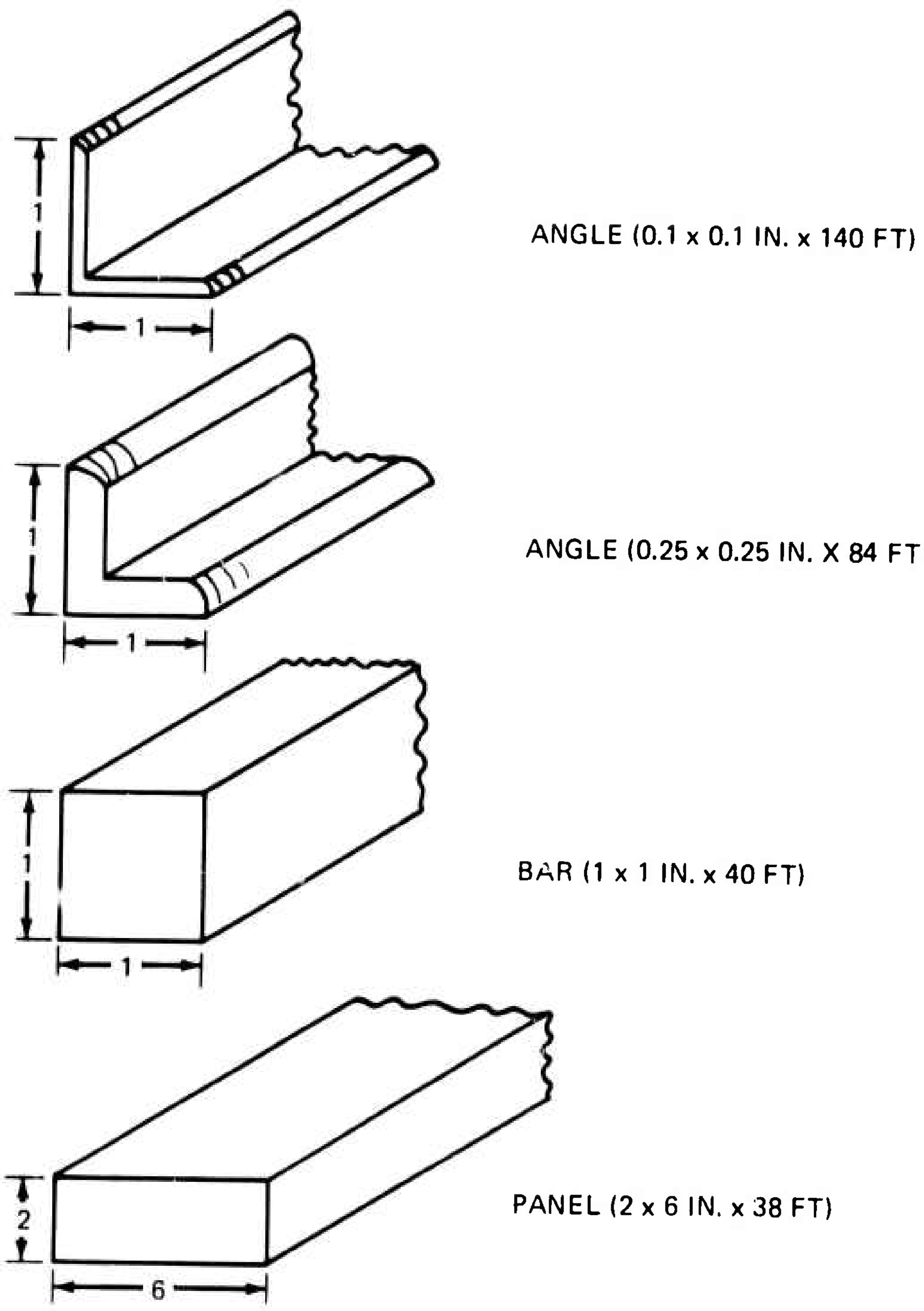


Figure 3. Shapes and Dimensions of Alloy 21 Extrusions

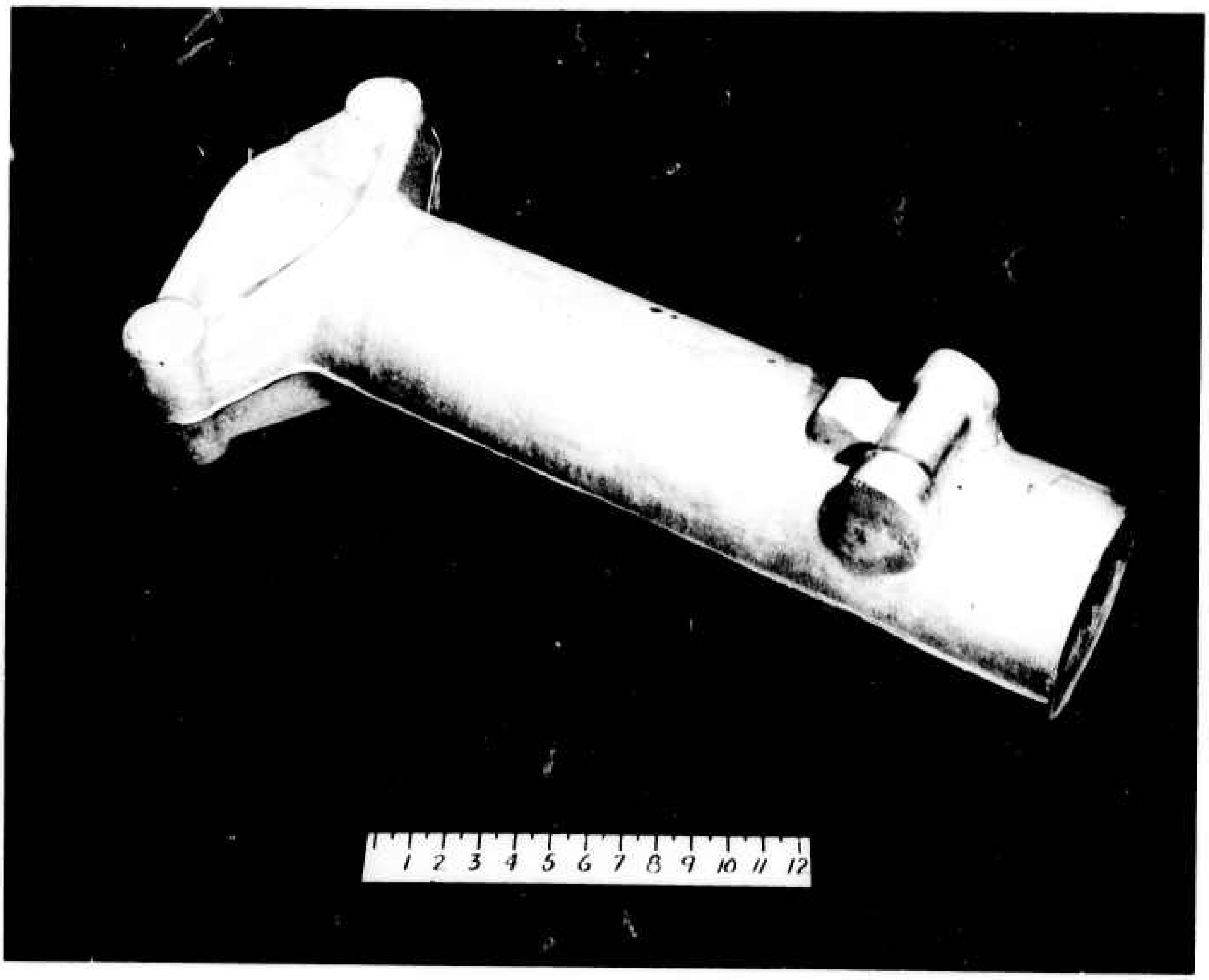


Figure 4. Landing Gear Die Forging of Alloy 21. The Forging Is 6.75 Inches in Diameter by 33 Inches Long (Three Each).

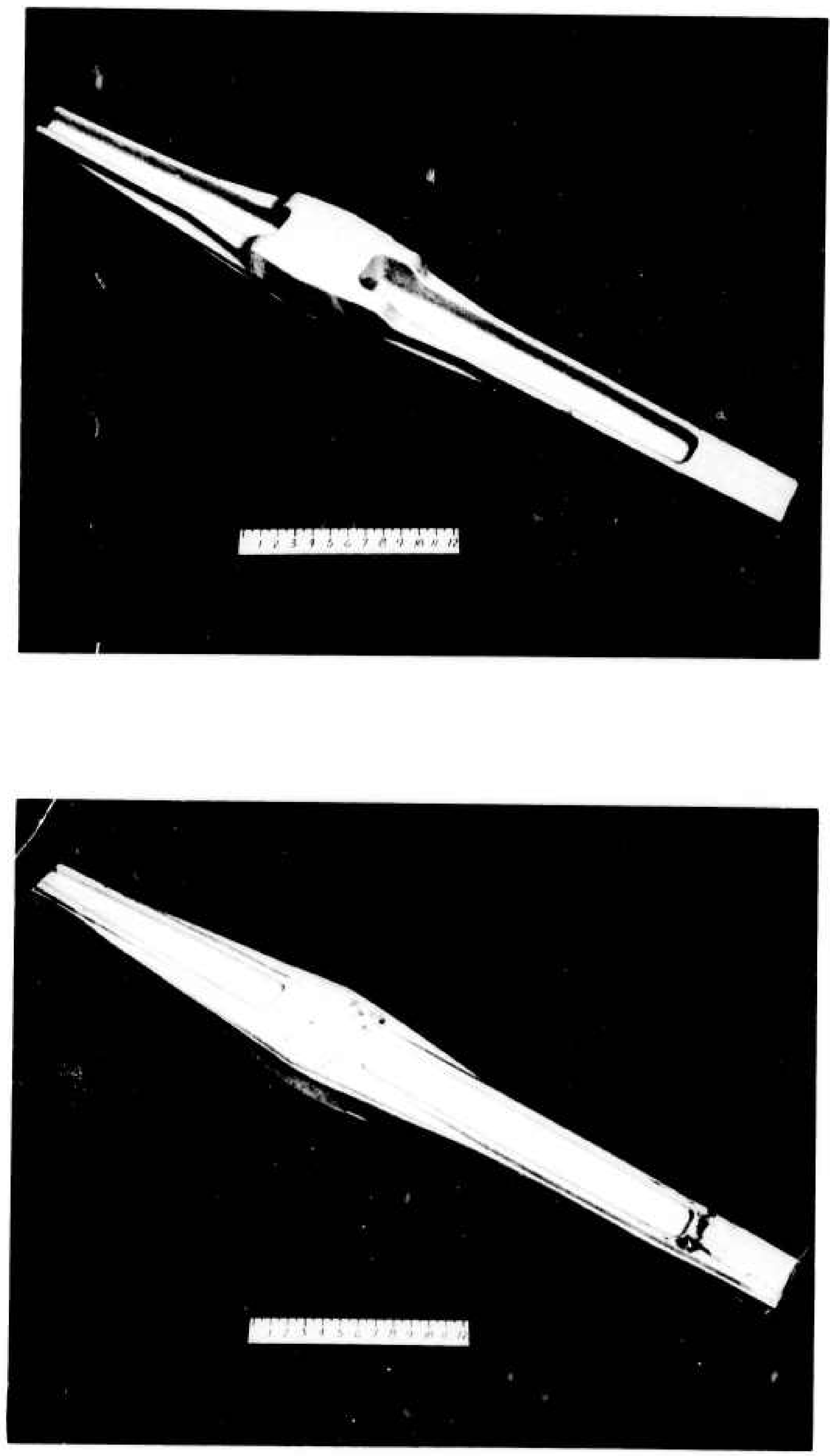


Figure 5. Top and Bottom of Navajo Die Forging of Alloy 21. The Forging Is 55 Inches Long and Ranges in Thickness from 0.62 to 4 Inches (Three Each).

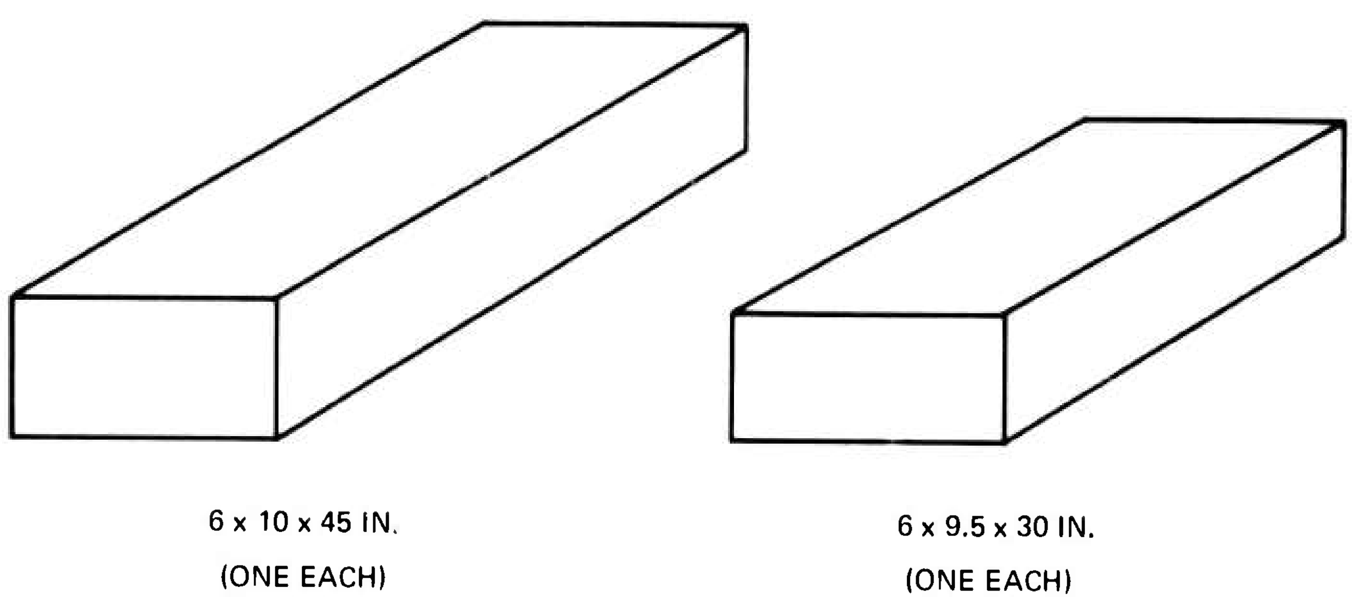


Figure 6. Shapes and Dimensions of Alloy 21 Hand Forgings

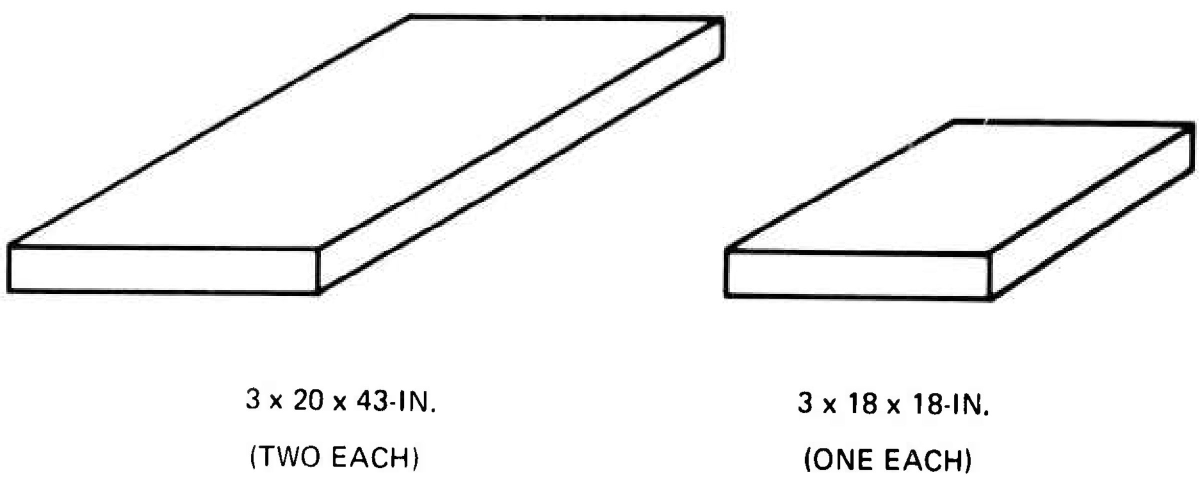


Figure 7. Shapes and Dimensions of Alloy 21 Plates

SECTION III

SELECTION OF THE HEAT TREATMENT FOR ALLOY 21

1. PHASE I

a. Effect of Quench Rate and Room-Temperature Delay Time on Mechanical Properties

Since it is known that quench rate and room-temperature delay time between quenching and artificial aging can have a significant effect on mechanical properties, these variables were studied first. Material from 3-in.-thick plate of alloy 21 was used for this study.

An outline of the heat-treatment schedule to evaluate the effects of quench rate and room-temperature delay time is shown in Fig. 8. To achieve the different quench rates, the block sizes and quenching conditions of Elkington and Turner (22) were used, as shown in Table 3. After a prior T6 treatment (24 hr at 250°F), all blanks were overaged at 320° to 325°F to an electrical conductivity of 38% IACS. This was done to ensure that the mechanical properties to be determined would be representative of material that had been sufficiently overaged to provide fairly high stress-corrosion resistance (7075-T73 has an electrical conductivity of 38% to 42% IACS). Hardness and electrical conductivity data were obtained on the variously quenched blanks as a function of aging time at 320° to 325°F by removing the blanks from the furnace after each 6 to 8 hr of aging. These data are plotted in Fig. 9 and listed in Tables 23 and 24, Appendix I.

The reason for the slight irregularity in hardness at 36 hr (Fig. 9A) is not clear. Figure 9B shows that a total of 46 hr of overaging after the T6 treatment was required in the most slowly quenched blanks to achieve 38% IACS. For the more rapidly quenched blanks, a total of 54 hr of overaging was required to reach 38% IACS. This behavior is quite different from that of 7075-T6, in which an electrical conductivity of 38% to 42% is reached after only about 24 to 30 hr of overaging at 325°F. To determine the effect of 10°F and 30°F increases in aging temperature on aging behavior, additional aging data at 320°F, 330°F, and 350°F were obtained. These results are shown in Fig. 10. Even at 350°F, 13 hr are required to reach an electrical conductivity of 38% IACS. For 7075, only about 6 to 8 hr at 350°F after a prior T6 treatment are required to reach 38% IACS.

The short-transverse mechanical-property data obtained from the blanks heat-treated in Phase I are listed in Table 25, Appendix I, and plotted in Fig. 11. The results show that room-temperature delay time had very little effect on mechanical properties. The effect of quench rate on mechanical properties was as expected, with strength being highest for the most rapid quench rate (180°F/sec). Elongation and reduction in area values were significantly higher for the most rapid quench condition.

b. Effect of Quench Rate on Ductility

The difference in elongation and reduction in area for the variously quenched specimens was also evident from an examination of the fractured tension specimens. Specimens from the slowly quenched blanks had macroscopically flat fractures normal to the tensile

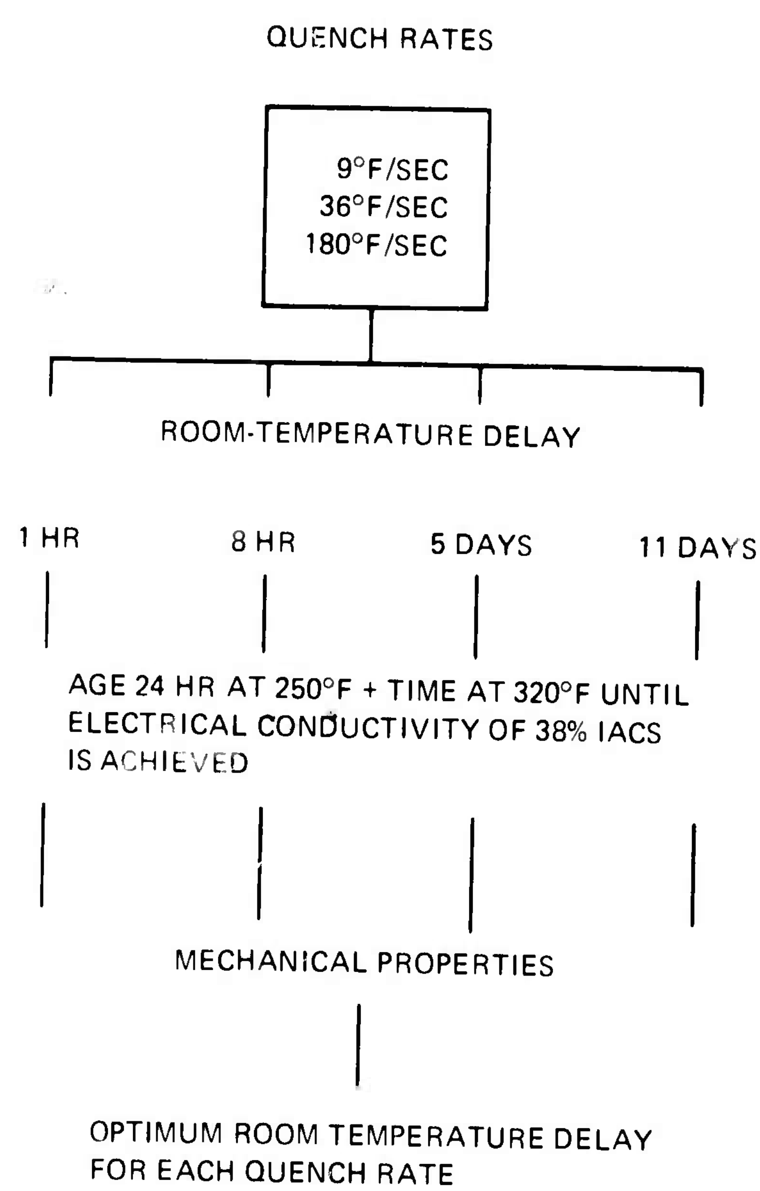


Figure 8. Outline for Phase I of the Heat-Treat Schedule to Evaluate the Effects of Quench Rate and Room-Temperature Delay Time on Mechanical Properties of Alloy 21

Table 3. Block Sizes and Quenching Conditions for Achieving Various Quench Rates[a] *(From Ref. 22)*

Quenching rate (°F/sec)	Block size (in.)	Quenching conditions
1.8	3 x 2-1/2 x 1-5/8	Cold air blast
9	3 x 2-1/2 x 1-1/4	Boiling water
36	3 x 2-1/2 x 1-1/4	Water at 194°F
90	3 x 5/8 x 5/8	Water at 194°F
180	3 x 5/8 x 5/8	Water at 140°F

[a]Quench rates are in the range 779° to 383°F.

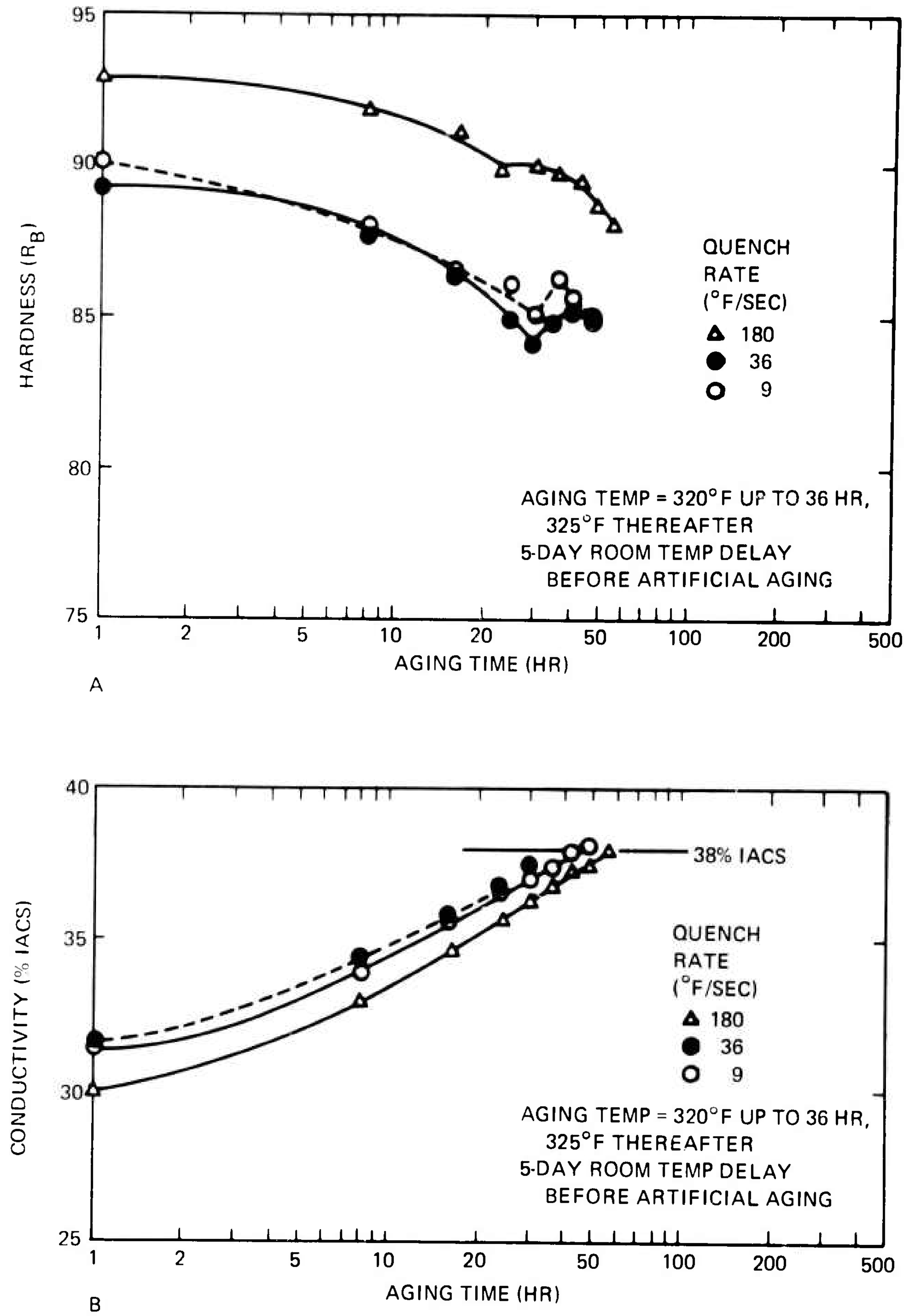


Figure 9. Effect of Quench Rate and Aging Time on Hardness (A) and Electrical Conductivity (B) of Alloy 21 after T6 Treatment (24 Hr at 250°F)

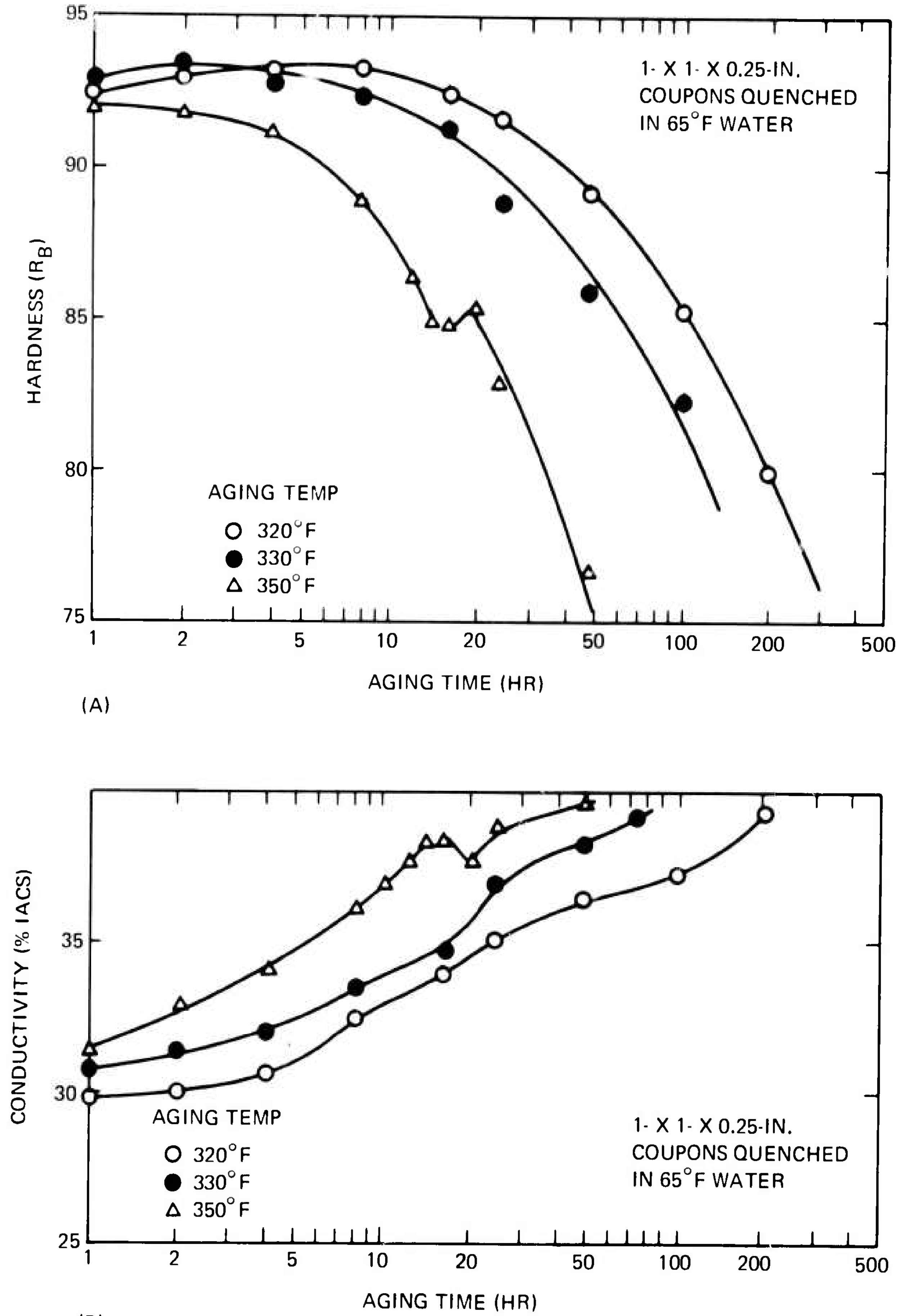


Figure 10. Effect of Aging Temperature and Time on Hardness (A) and Electrical Conductivity (B) of Alloy 21 after T6 Treatment (24 Hr at 250° F)

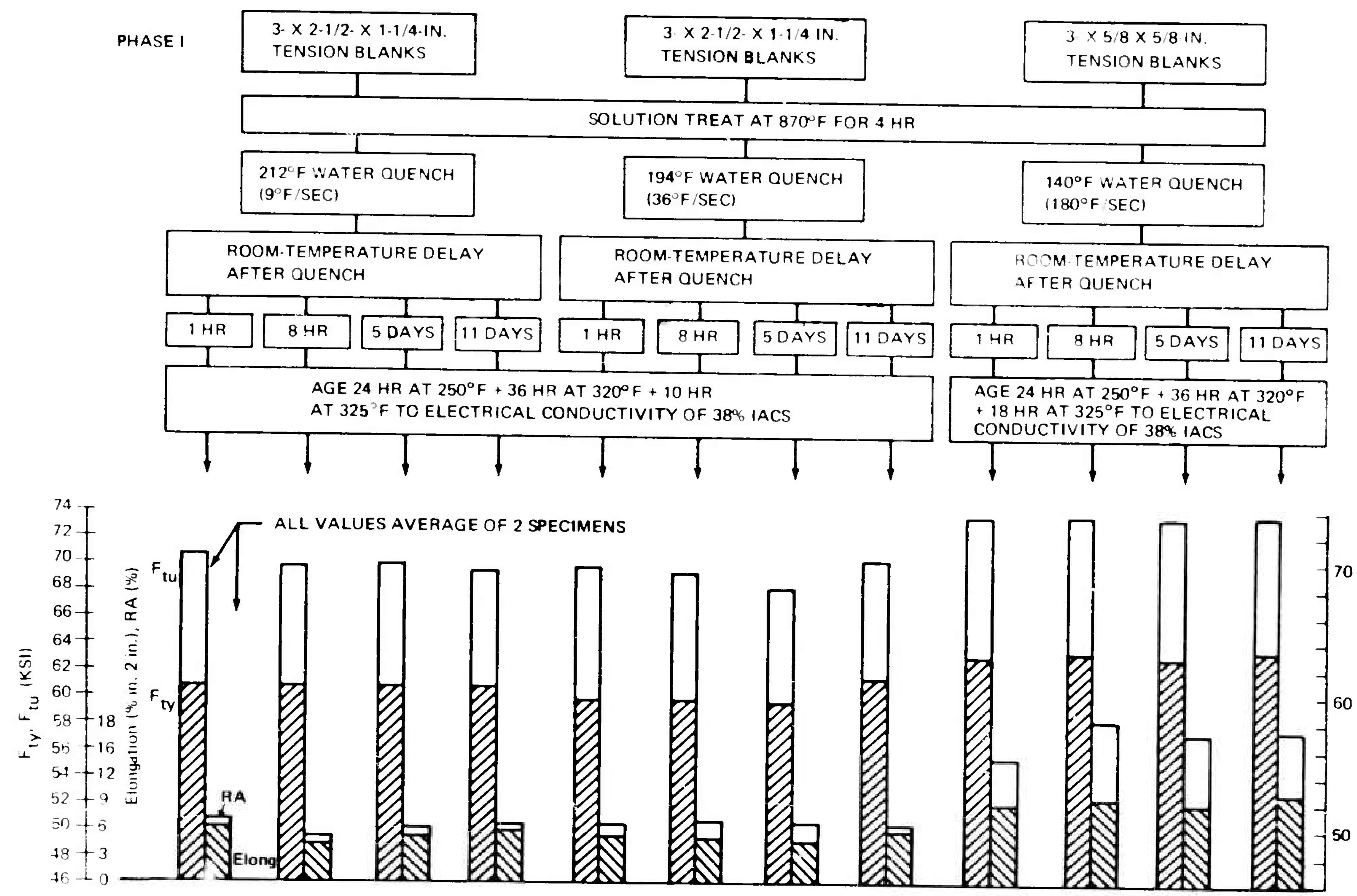


Figure 11. Effect of Quench Rate and Room-Temperature Delay Time on Short-Transverse Mechanical Properties of Alloy 21

axis, whereas the most rapidly quenched specimens showed 45° shear fractures (Fig. 12). Additional optical and electron microscopy studies on failed tension specimens from the slowly quenched blanks showed a tendency toward intergranular fracture (Fig. 13), with a high density of intermetallic particles present on the fracture face (Fig. 14). These particles are probably equilibrium M ($MgZn_2$) phase. Other unidentified and larger intermetallic particles also played a role in initiating fracture in these specimens (Fig. 15), but there is no evidence that these larger intermetallics did not also aid in initiating fracture in the more rapidly quenched material. Fractures in specimens from the more rapidly quenched blanks were more transgranular (Fig. 16), and fractography of these specimens showed both transgranular and intergranular dimples and brittle intergranular fracture (Fig. 17).

An additional and less frequently observed type of intermetallic particle noted in tension specimens from blanks quenched at all rates is shown in Fig. 18. Microprobe analysis of these particles (Table 4) showed them to have a composition approximating that of $ZrAl_3$. It is believed these particles are the same as those shown in the etched micrographs of the 14-in.-diam as-cast and homogenized ingot shown in Fig. 2. Although these intermetallic particles had no noticeable effect on the properties of alloy 21, they are certainly not desirable. Further casting technology could undoubtedly eliminate the occurrence of these intermetallics.

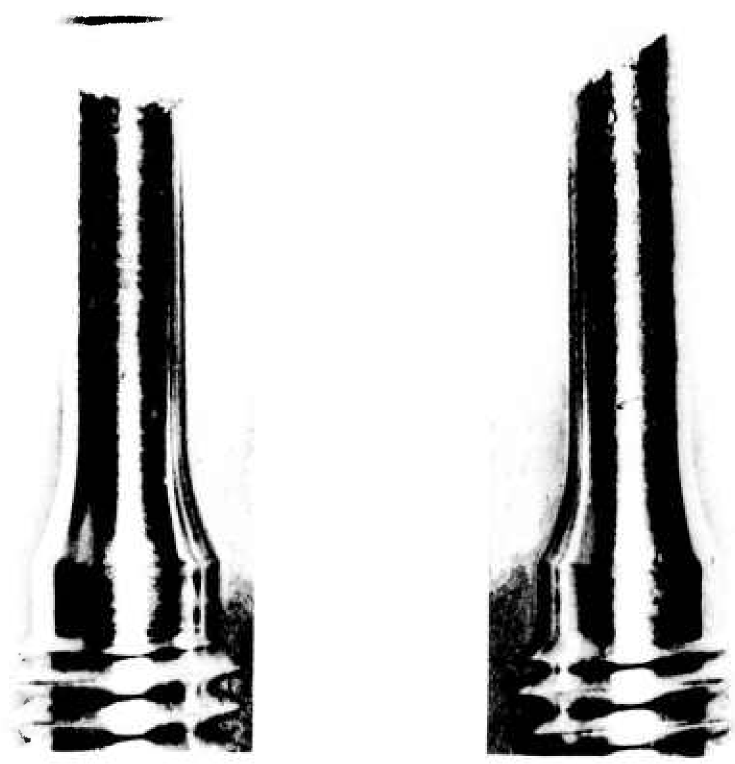
Transmission electron micrographs from aged blanks of alloy 21 that had been quenched at 9°F/sec and 180°F/sec were similar except for a higher density of large rod-shaped particles in the slowly quenched material (Fig. 19). These larger particles may be the same ones that appear as small dots on the micrographs of the slowly quenched, unetched material in Fig. 15. Such particles may be responsible for the darker etching response of the slowly quenched material compared with that of the more rapidly quenched material (Figs. 13 and 16). Attempts to identify this phase by transmission electron microscopy techniques were unsuccessful.

2. PHASE II

a. Effect of Quench Rate and Overaging Time on Mechanical Properties

After it was determined that room-temperature delay time between quenching and artificial aging had little effect on mechanical properties (Fig. 11), a study was conducted to select a heat treatment for alloy 21 that would provide the highest mechanical properties and at the same time meet the stress-corrosion goal of the contract. In particular, the degree of overaging was to be selected on the basis of stress-corrosion crack growth rate data; that is, the strength of alloy 21 was to be governed by the amount of overaging required to achieve the stress-corrosion resistance goal.

For this study, blanks from 3-in.-thick plate of alloy 21 were machined and quenched at four different rates. These blanks were for short-transverse tension and tension stress-corrosion specimens and for double cantilever beam stress-corrosion specimens, which will be discussed later. After quenching, all blanks were aged at room temperature for 1 hr, then aged to the T6 temper (24 hr at 250°F). The blanks were then given a second aging treatment at either 325°F or 350°F for various times. This heat-treatment schedule is shown in Fig. 20, along with the outlined test program for Phase II.



SPECIMEN 1A
3- X 2-1/2- X 1-1/4-IN. BLANK
212°F WATER QUENCH
(9°F/SEC QUENCH RATE)

SPECIMEN 59
3- X 5/8- X 5/8-IN. BLANK
140°F WATER QUENCH
(180°F/SEC QUENCH RATE)

Figure 12. Fracture Profiles of Short-Transverse Tension Specimens from Quenched Blanks of Alloy 21. Slowly Quenched Specimen 1A Exhibited Flatter Fracture and Lower Ductility Than More Rapidly Quenched Specimen 59.

Figure 13. Fracture Profile of Tension Specimen 1A (Shown in Figure 12), Illustrating a Tendency toward Intergranular Fracture. Keller's Etchant (200X).

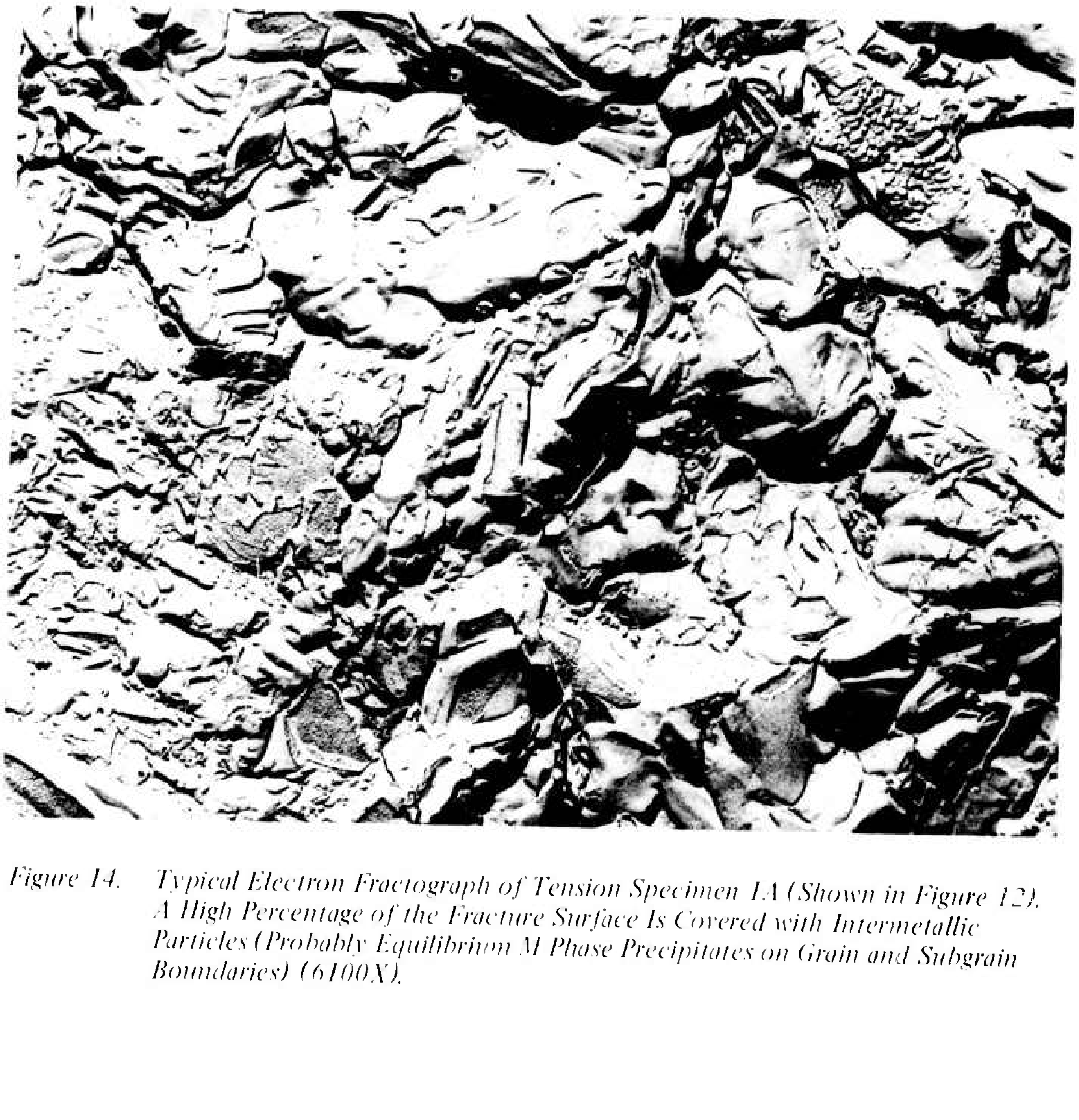


Figure 14. Typical Electron Fractograph of Tension Specimen 1A (Shown in Figure 12). A High Percentage of the Fracture Surface Is Covered with Intermetallic Particles (Probably Equilibrium M Phase Precipitates on Grain and Subgrain Boundaries) (6100X).

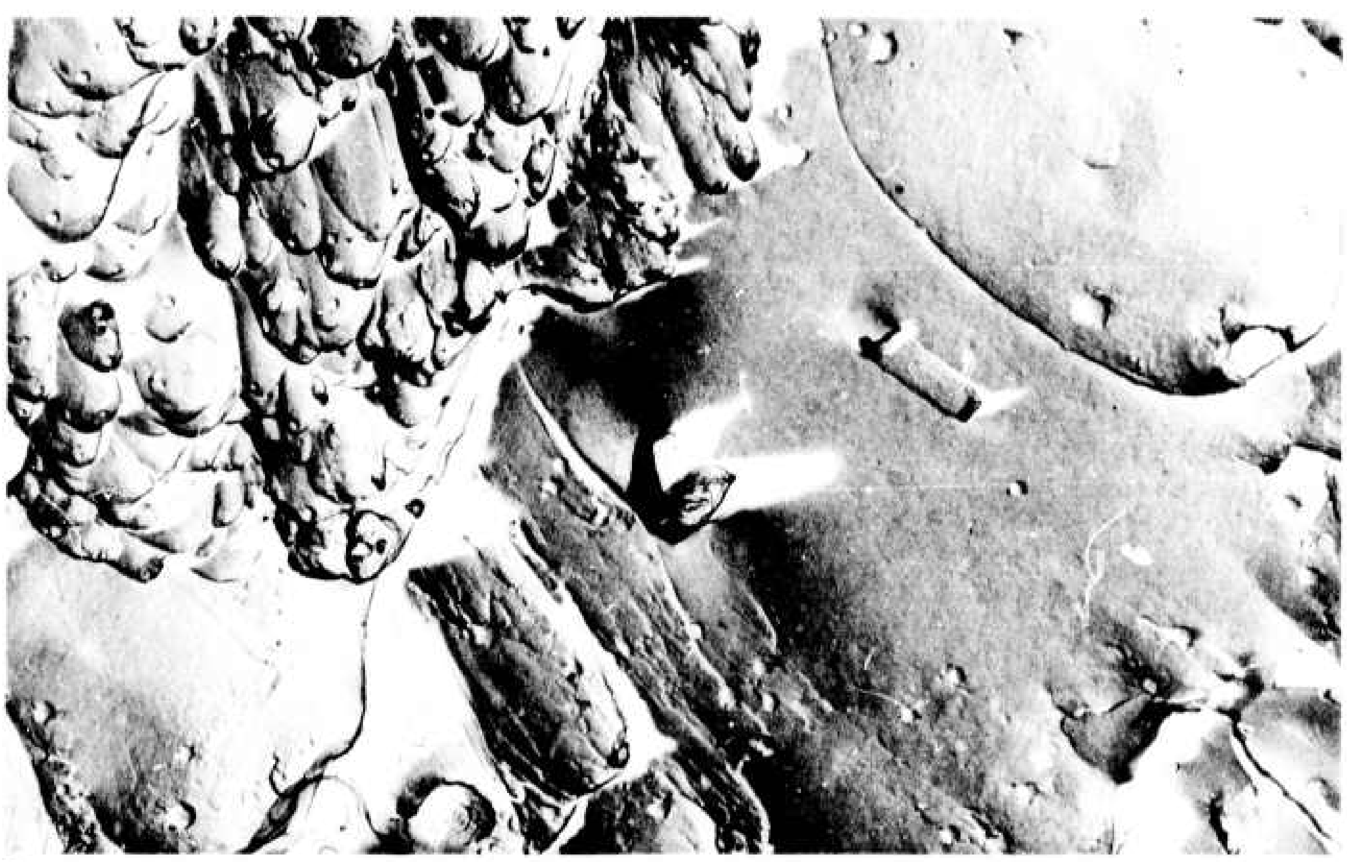
A. UNETCHED (500X)

B. UNETCHED (700X)

Figure 15. Fracture Profiles of Tension Specimen 1A (Shown in Figure 12), Illustrating the Influence of Intermetallic Particles on the Fracture Behavior

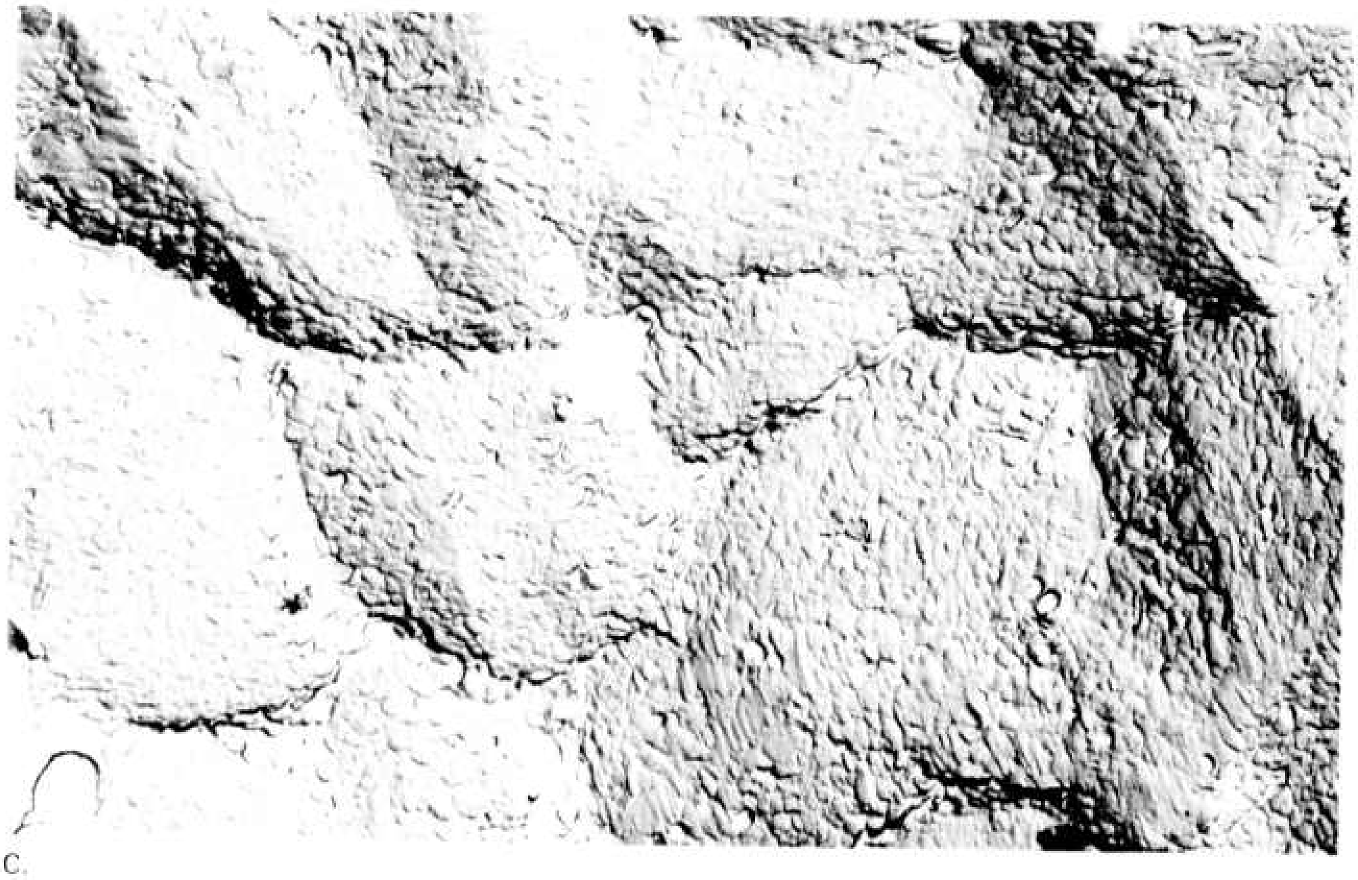
Figure 16. Fracture Profile of Tension Specimen 59 (Shown in Figure 12). Compared with Specimen 1A, a Larger Portion of the Fracture in Specimen 59 Was Transgranular. Keller's Etchant (200X).

A.



B.

Figure 17. Typical Electron Fractographs of Tension Specimen 59 (Shown in Figure 12). Fracture Features on This Specimen Showed Small and Large Transgranular Dimples (A and B), Intergranular Dimples (C), and Intergranular Fracture (D) (6100X).



C.

D.

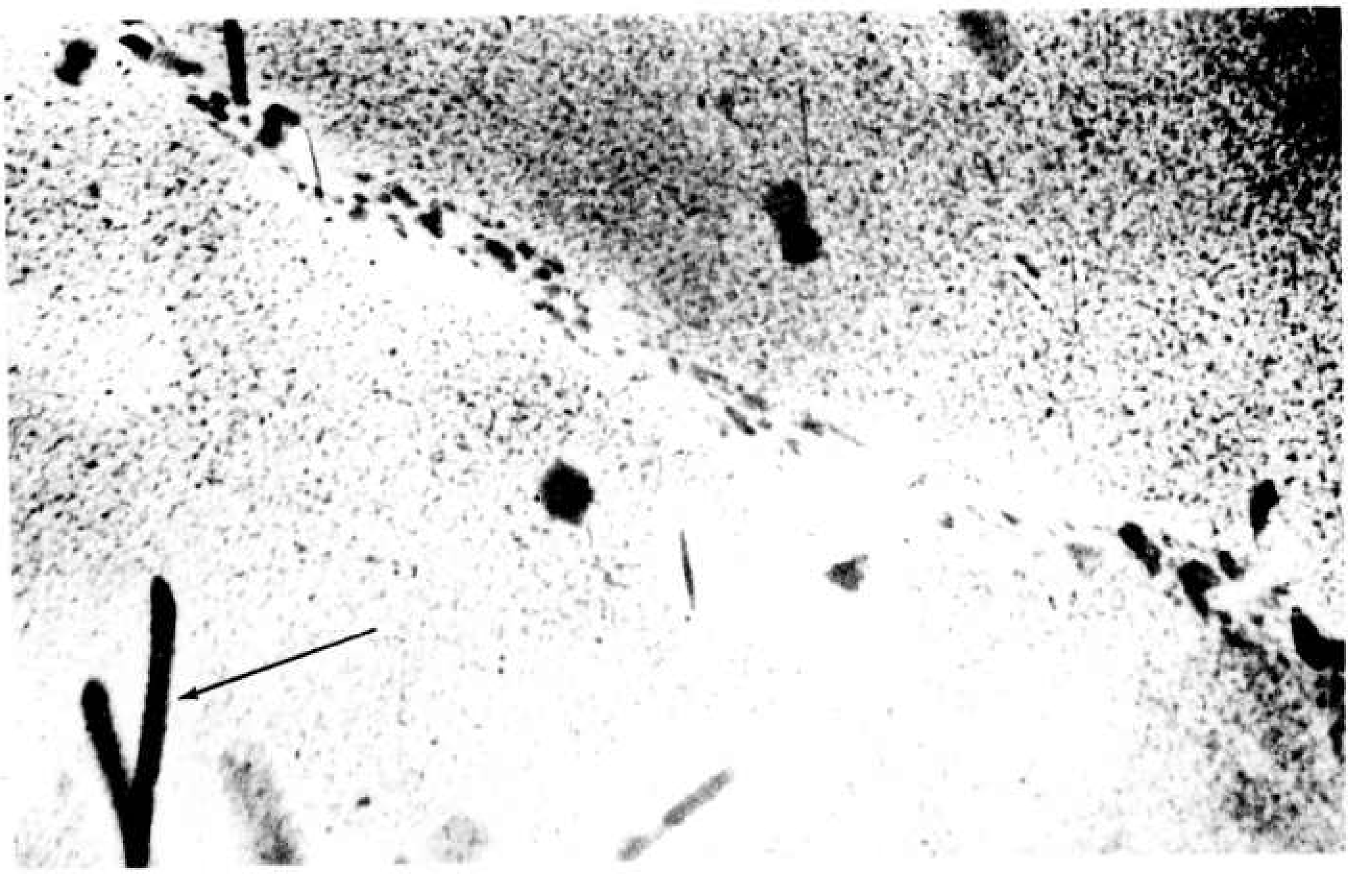
Figure 17. (Concluded)

Figure 18. Typical Zirconium-Bearing Intermetallic Particles Observed in Wrought Products of Alloy 21. Unetched (500X).

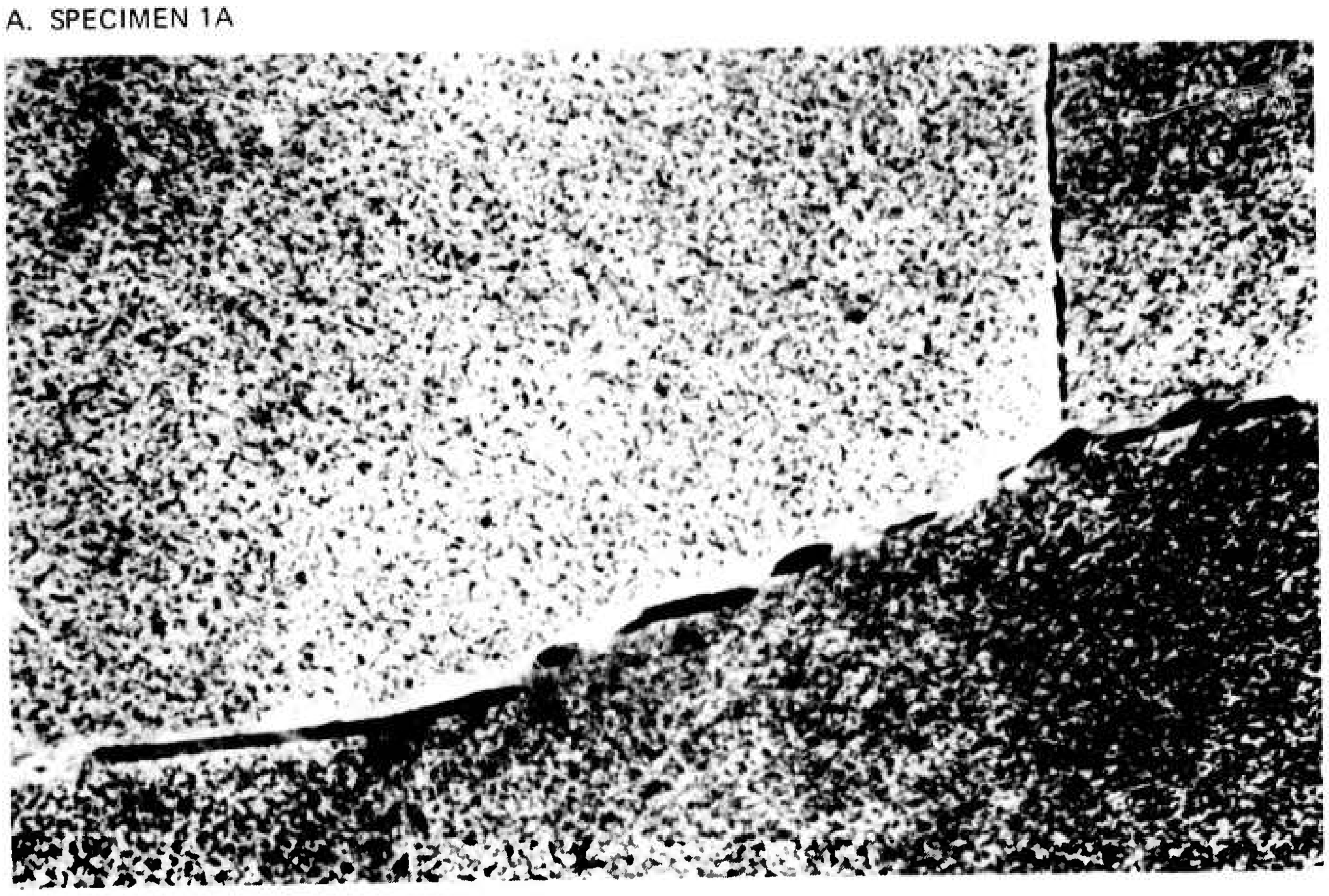
Table 4. Electron Microprobe Analysis of Intermetallic Particles Observed in Alloy 21

	Zn	Mg	Cu	Fe	Si	Mn	Zr	Al	Total
Particle	2.26	0.48	0.19	1.91	N.D.*	N.D.*	42.51	54.93	102.18
Matrix	7.11	2.26	0.91	0.01	N.D.*	0.06	0.08	91.60	101.88

* None Detected



A. SPECIMEN 1A



B. SPECIMEN 59

Figure 19. Typical Transmission Electron Micrographs of Tension Specimens 1A and 59 (Shown in Figure 12). Note the Large Rod-Shaped Particles (Arrow) in the Slowly Quenched Material (A) (45,000X).

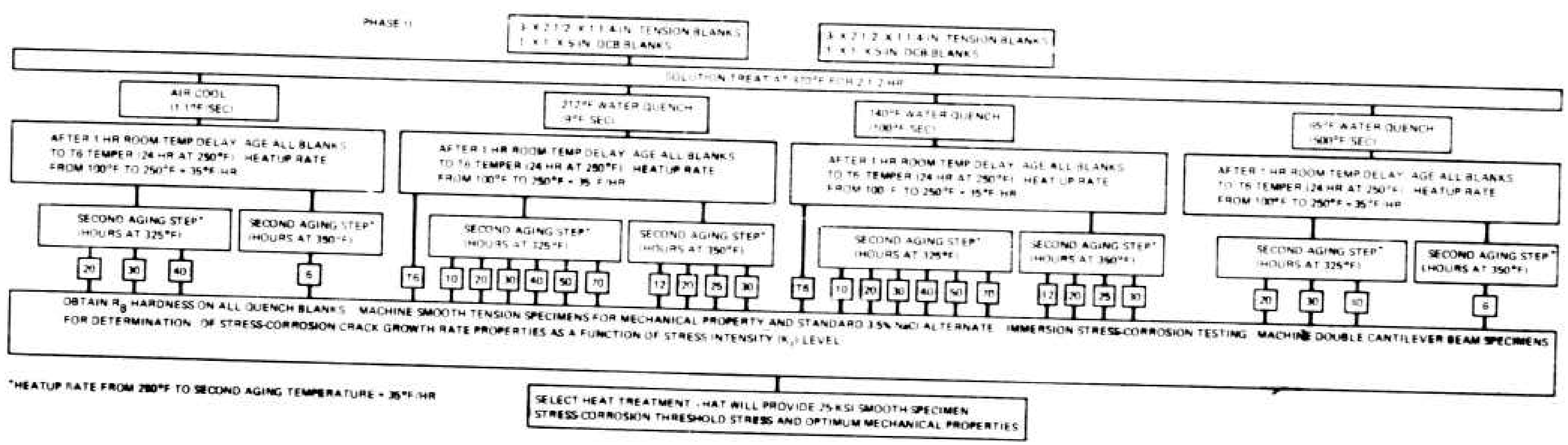


Figure 20. *Program Outline for Phase II Study to Determine Optimum Heat Treatment for Alloy 21*

The effects on hardness of quench rate and of aging time at 325°F and 350°F after a prior T6 treatment are shown in Figs. 21 and 22. As expected, hardness decreased with decreasing cooling rate. The effects on short-transverse yield strength and elongation of quench rate and of aging time at 325°F and 350°F after a prior T6 treatment may be seen in Figs. 23 and 24. The general trend toward decreased elongation as quench rate decreases, noticeable in Figs. 23 and 24, was also observed during the Phase I study on the effect of room-temperature delay times on mechanical properties (Fig. 11). Hardness and mechanical-property data for this study are tabulated in Table 26, Appendix II.

Note in Figs. 23 and 24 that the most rapid quench rate, 500°F/sec, generally resulted in lower yield strength than the 100°F/sec quench rate. This was certainly not expected, and the data points for the 500°F/sec quench were considered suspect. To check that possibility, hardness data obtained on the original tension specimen blanks were plotted against the yield strength data for all Phase II tension specimens. This plot, shown in Fig. 25, indicates that the tensile properties in question are probably in error. An upward correction was made in the yield strength of the specimens quenched at 500°F/sec, based on Fig. 25. These adjusted data are also plotted in Figs. 23 and 24. The reason for the low yield strengths of the most rapidly quenched specimens is not clear. It is possible that these specimens, machined as a batch and at a different time than the other specimens, were overheated during machining.

The temperature selected for the second step of the two-step aging treatment of alloy 21 was 325°F rather than 350°F because overaging kinetics are slower at 325°F. (The more rapid rate of overaging at 350°F would make furnace times during aging more critical and would require much closer furnace control during the aging cycle.) Thus, the short-transverse mechanical properties for any given quench rate and degree of overaging of alloy 21 may be determined from Fig. 23.

b. Effect of Quench Rate and Overaging Time on Stress-Corrosion Crack Growth Rate Properties

To obtain stress-corrosion crack growth rate data for alloy 21 as a function of heat treatment, bolt-loaded double cantilever beam (DCB) specimens were used. The configuration of the DCB specimen used in this study is shown in Fig. 26. The DCB specimens were machined from the center of the 3-in.-thick plate material of alloy 21. The longitudinal direction of the DCB specimen was taken in the plate rolling direction. Notch orientation in these specimens was such that the cracks propagated along the midplane of the original plate (short-transverse loading).

Stress intensities for this DCB specimen can be calculated using a curve of compliance versus crack length and Eqs. (1) and (2) (from Ref. 23):

$$G = \frac{P^2}{2b}\,\frac{dc}{da} \qquad (1)$$

$$K_I = \sqrt{GE} \qquad (2)$$

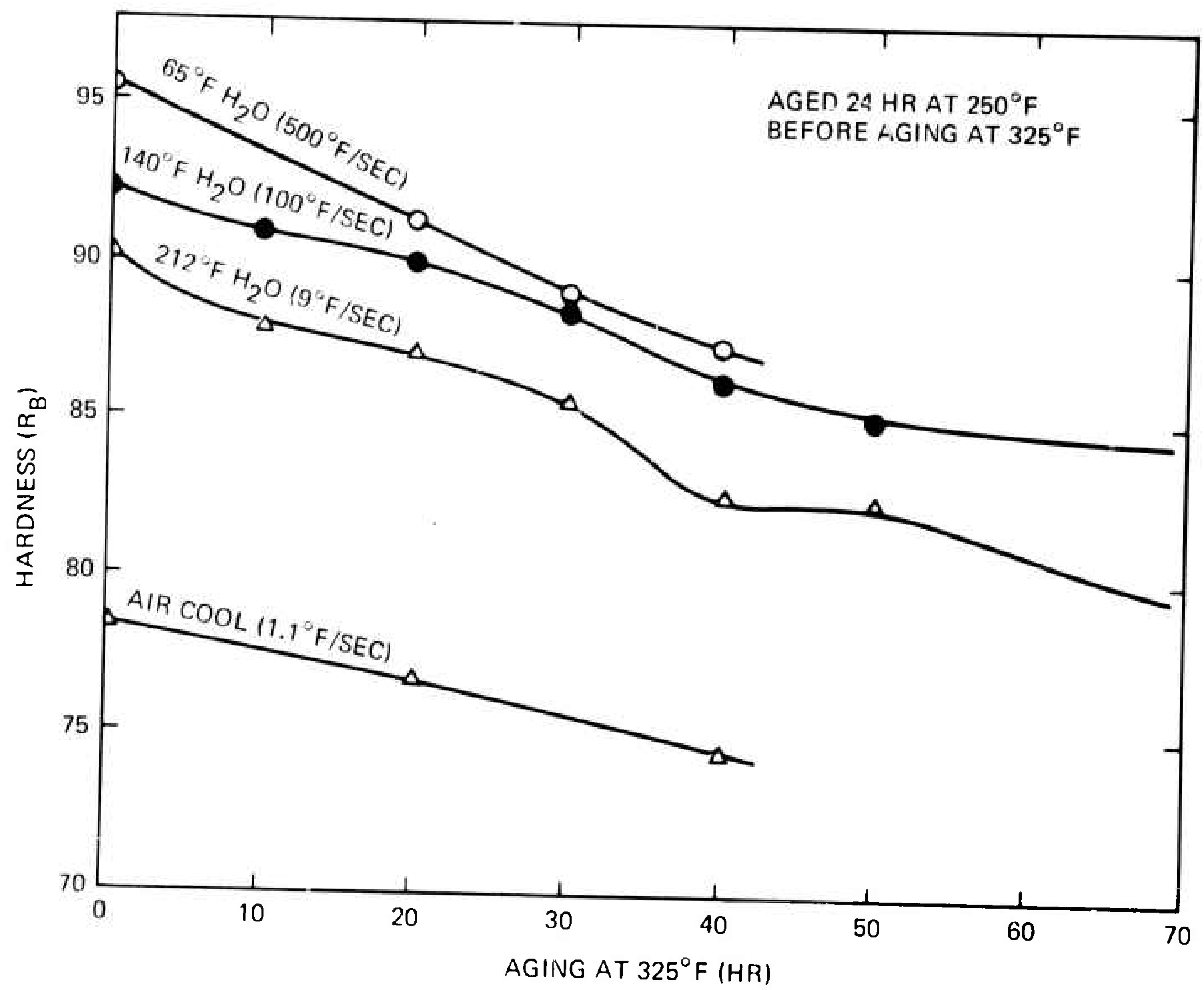


Figure 21. Effects of Quench Rate and Aging Time at 325°F on Hardness of Tension Specimen Blanks from 3-Inch-Thick Plate Evaluated in Phase II

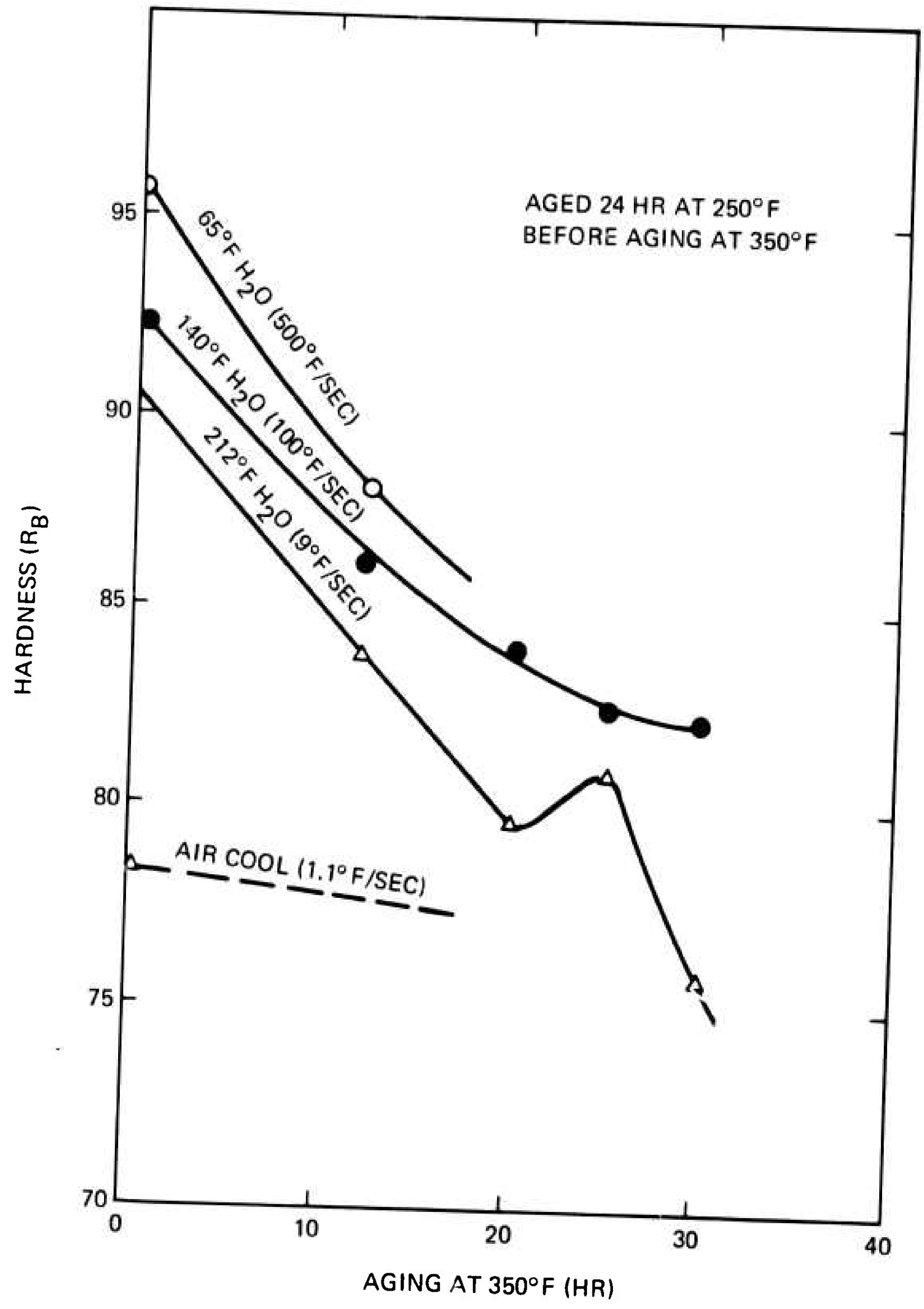


Figure 22. Effects of Quench Rate and Aging Time at 350°F on Hardness of Tension Specimen Blanks from 3-Inch-Thick Plate Evaluated in Phase II

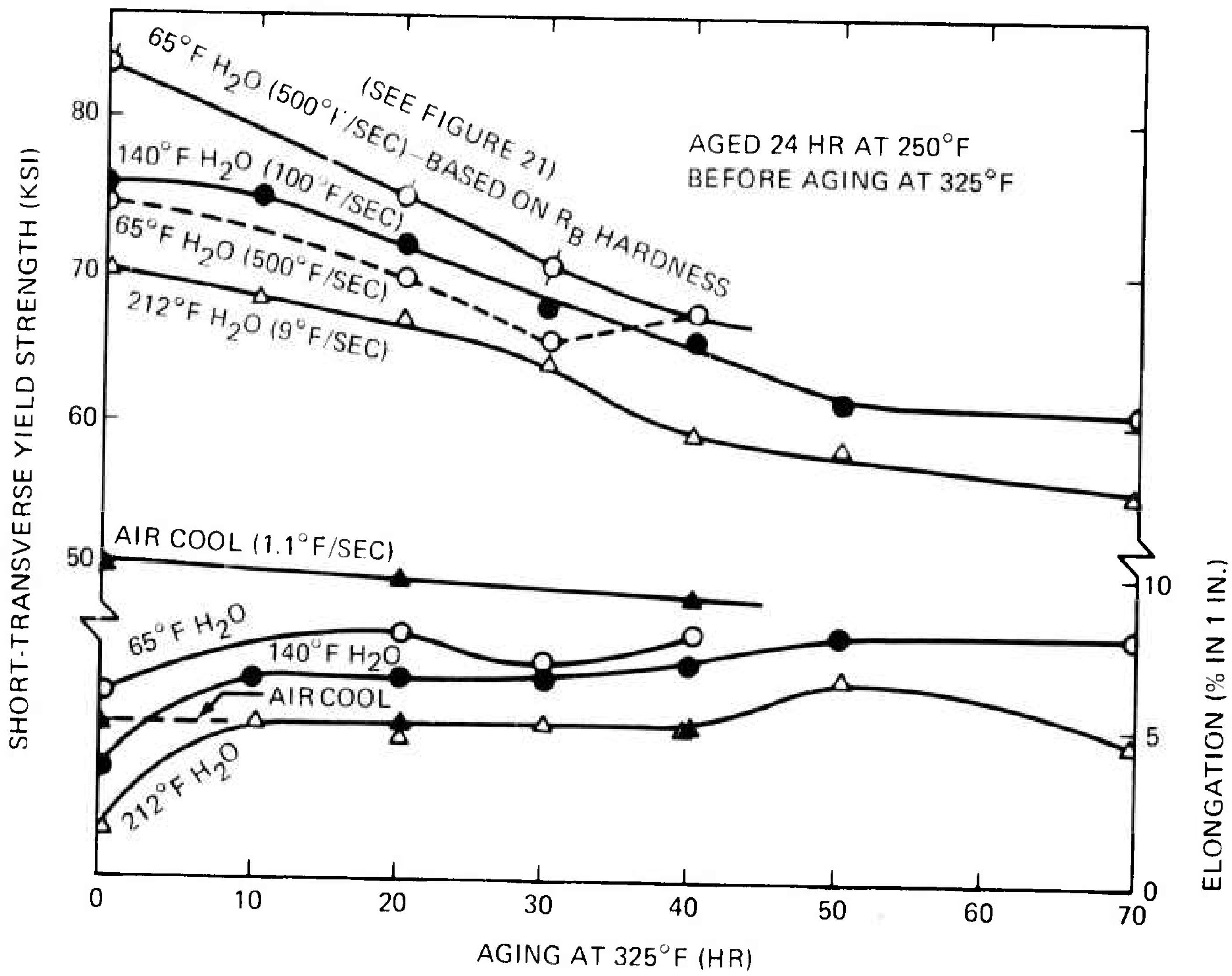


Figure 23. Effects of Quench Rate and Aging Time at 325°F on Short-Transverse Yield Strength of 3-Inch-Thick Plate Evaluated in Phase II

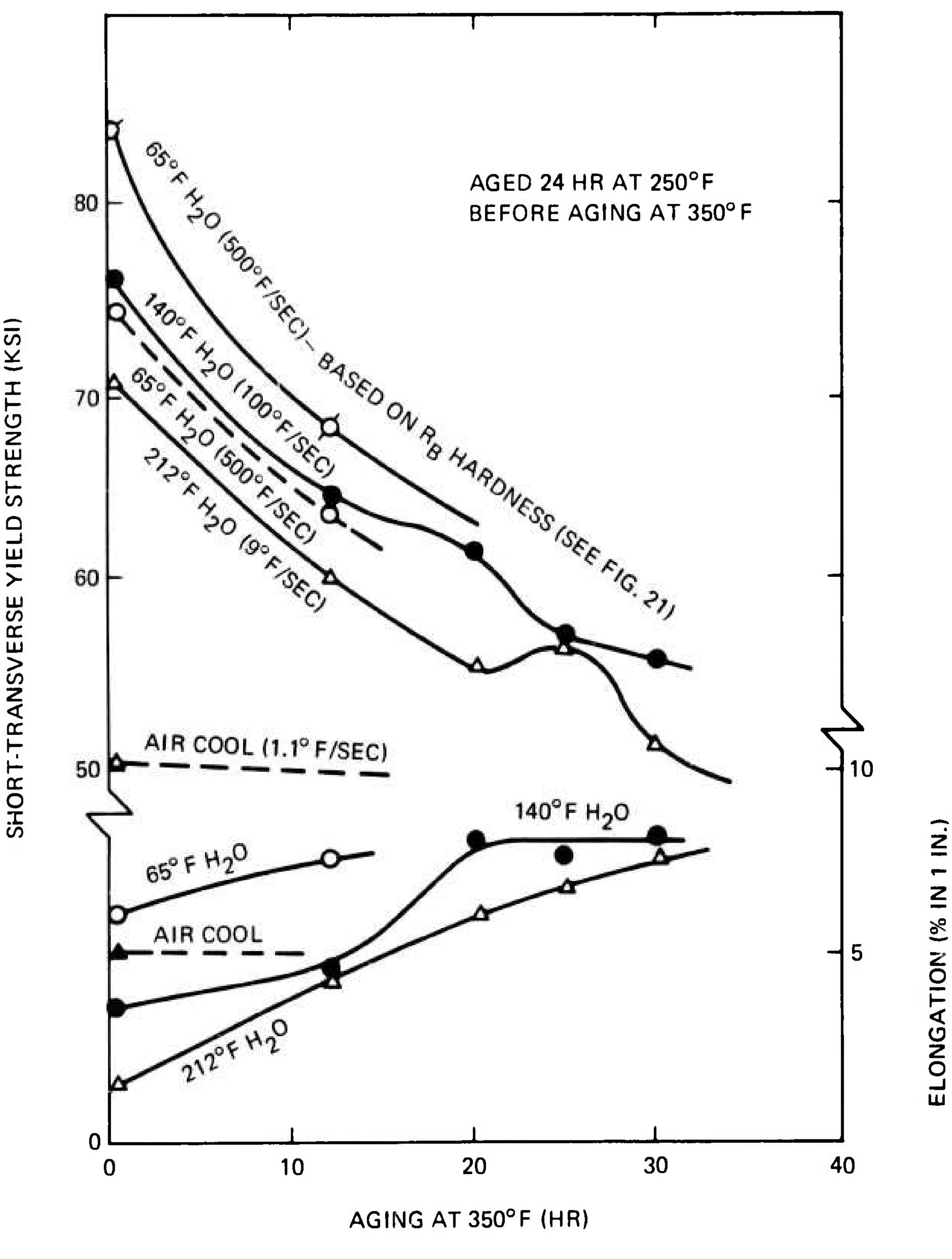


Figure 24. Effects of Quench Rate and Aging Time at 350°F on Short-Transverse Yield Strength of 3-Inch-Thick Plate Evaluated in Phase II

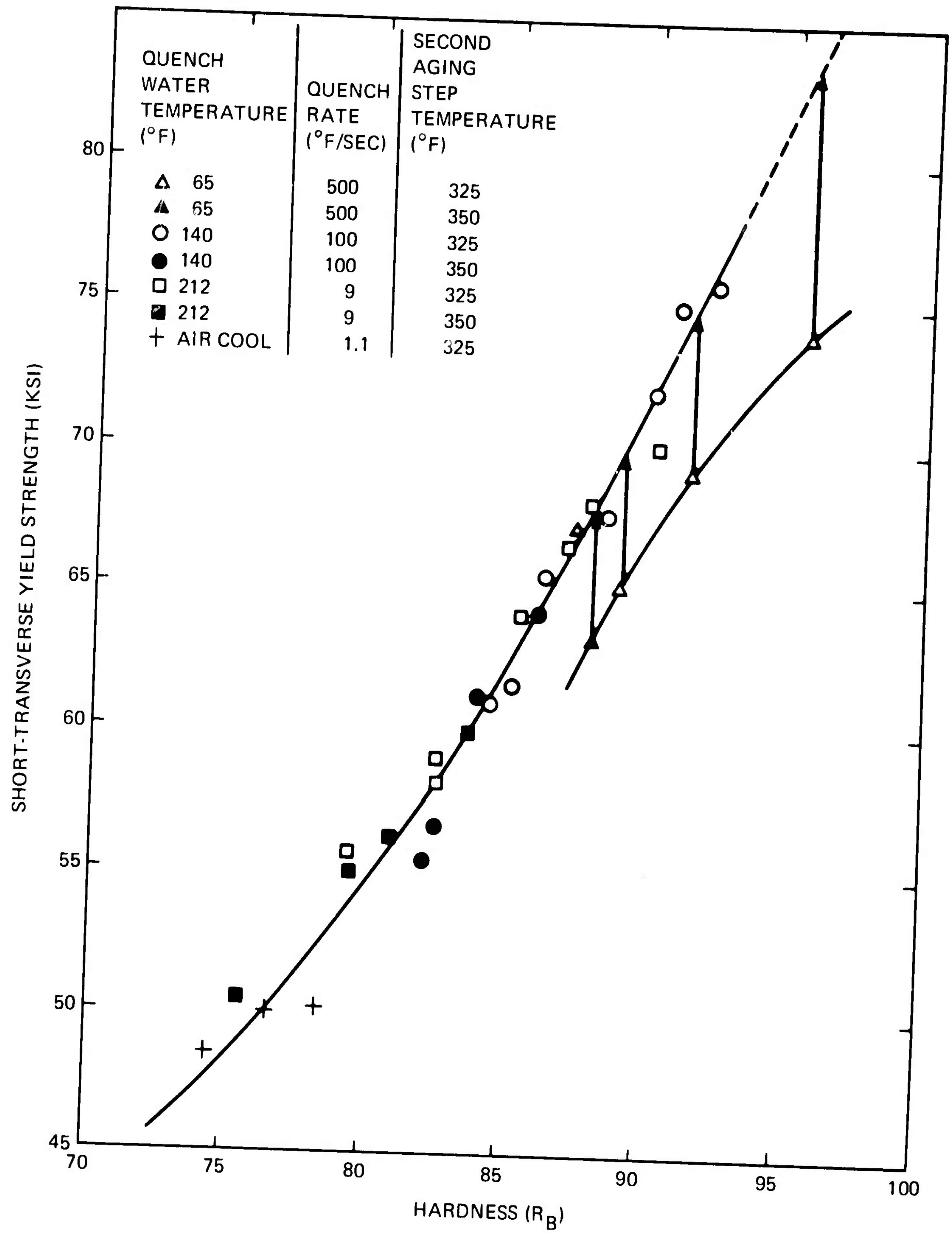


Figure 25. Correlation of Hardness and Short-Transverse Yield Strength of 3-Inch-Thick Plate Evaluated in Phase II

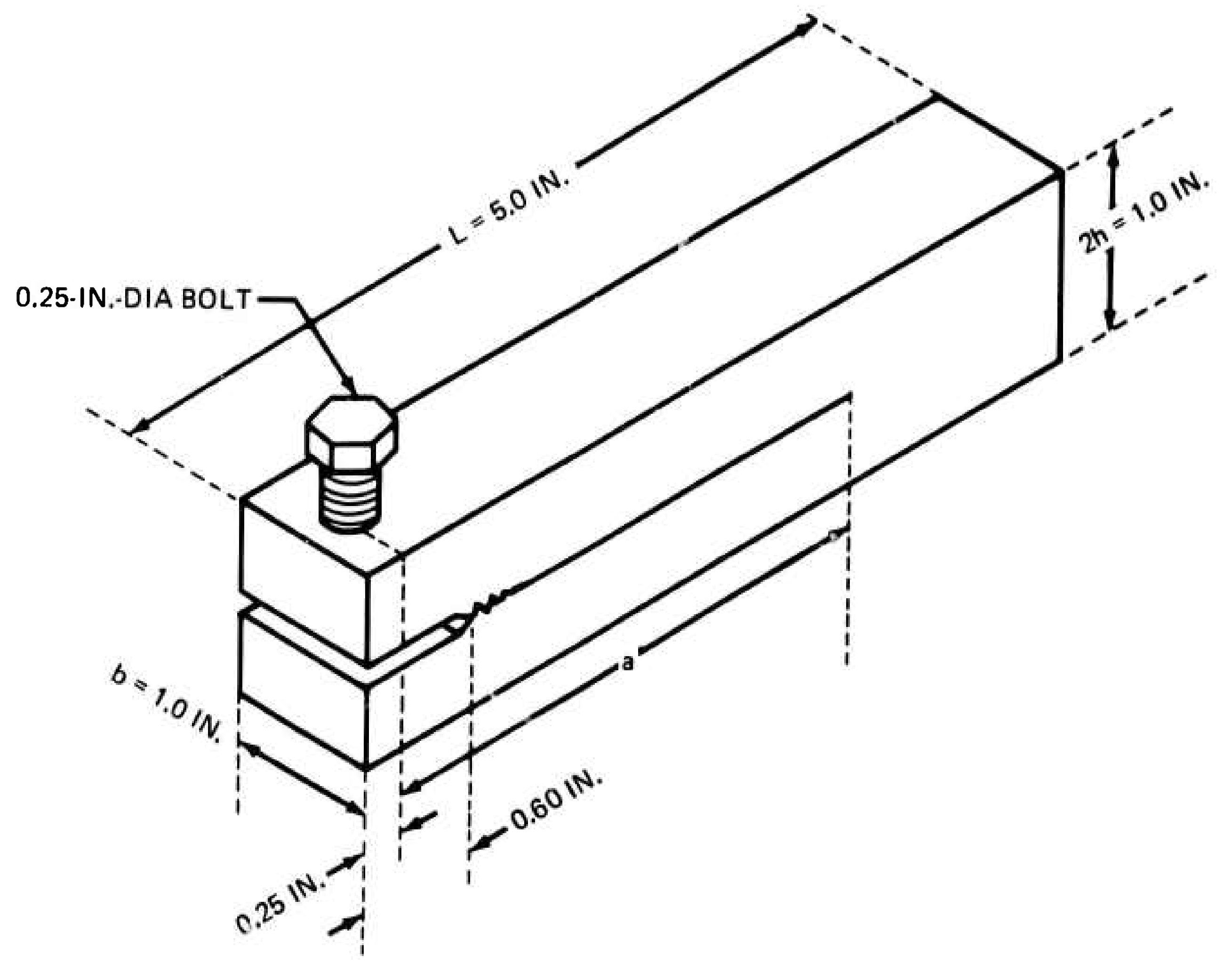


Figure 26. Double Cantilever Beam Specimen Used to Determine Stress-Corrosion Crack Growth Rates as a Function of Heat Treatment in Phase II Evaluation

where: G = crack extension force or strain energy release rate
P = load
b = specimen thickness
c = specimen compliance (reciprocal stiffness) when the crack length is a
a = crack length measured from load point (centerline of loading bolt)
E = modulus of elasticity (10.3×10^6 for aluminum alloys)

Or, an approximate analytical expression for compliance as a function of crack length can be obtained using beam theory. However, Mostovoy, Crosley, and Ripling (24), by performing experimental measurements of compliance on uniform DCB specimens, showed that in addition to the bending and shear deflections that may be calculated from beam theory, some deflection also occurs because of rotations at the assumed built-in end of the beam. By treating this contribution to compliance as an increase in crack length, Mostovoy et al. (24) arrived at the following expression for compliance:

$$c = \frac{2}{3EI} \left|(a + a_o)^3 + h^2 a\right| \tag{3}$$

where: I = moment of inertia of one of the arms = $bh^3/12$
a_o = an empirical rotation correction equal to 0.6h
h = 1/2 specimen height

They determined the value of a_o to be approximately 0.6h from calibration bars of heights from 4 to 1/2 in. over 10 in. of effective crack length. By differentiating Eq. (3) with respect to a, substituting into Eqs. (1) and (2), and noting that

$$P = \frac{v}{c} \tag{4}$$

where v is the total deflection of the two arms of the DCB specimen at the load point, the following expression for K_I was derived:

$$K_I = \frac{vEh\,[3h\,(a + 0.6h)^2 + h^3]^{1/2}}{4\,[(a + 0.6h)^3 + h^2 a]} \tag{5}$$

To perform a stress-corrosion test using bolt-loaded specimens, the loading bolt is turned until a crack is introduced at the end of the machined notch. For fixed displacement conditions at the bolt, K_I decreases rapidly as crack length increases (Fig. 27). Thus, the initial pop-in crack runs only a very short distance before arresting. By measuring the crack lengths and corresponding v values for subsequent pop-ins, a series of K_{Ic} values can be calculated using Eq. (5). Hoagland has used a similar specimen with Instron loading to obtain many K_{Ic} data points from a single DCB specimen (25). For some alloys, crack advance during pop-in is extremely short. Thus, the stress intensity at the crack tip is almost continuously at K_{Ic} during crack advancement by pop-in. For these alloys, a crack length and v reading at any point during crack advance by bolt loading will give a K_{Ic} value.

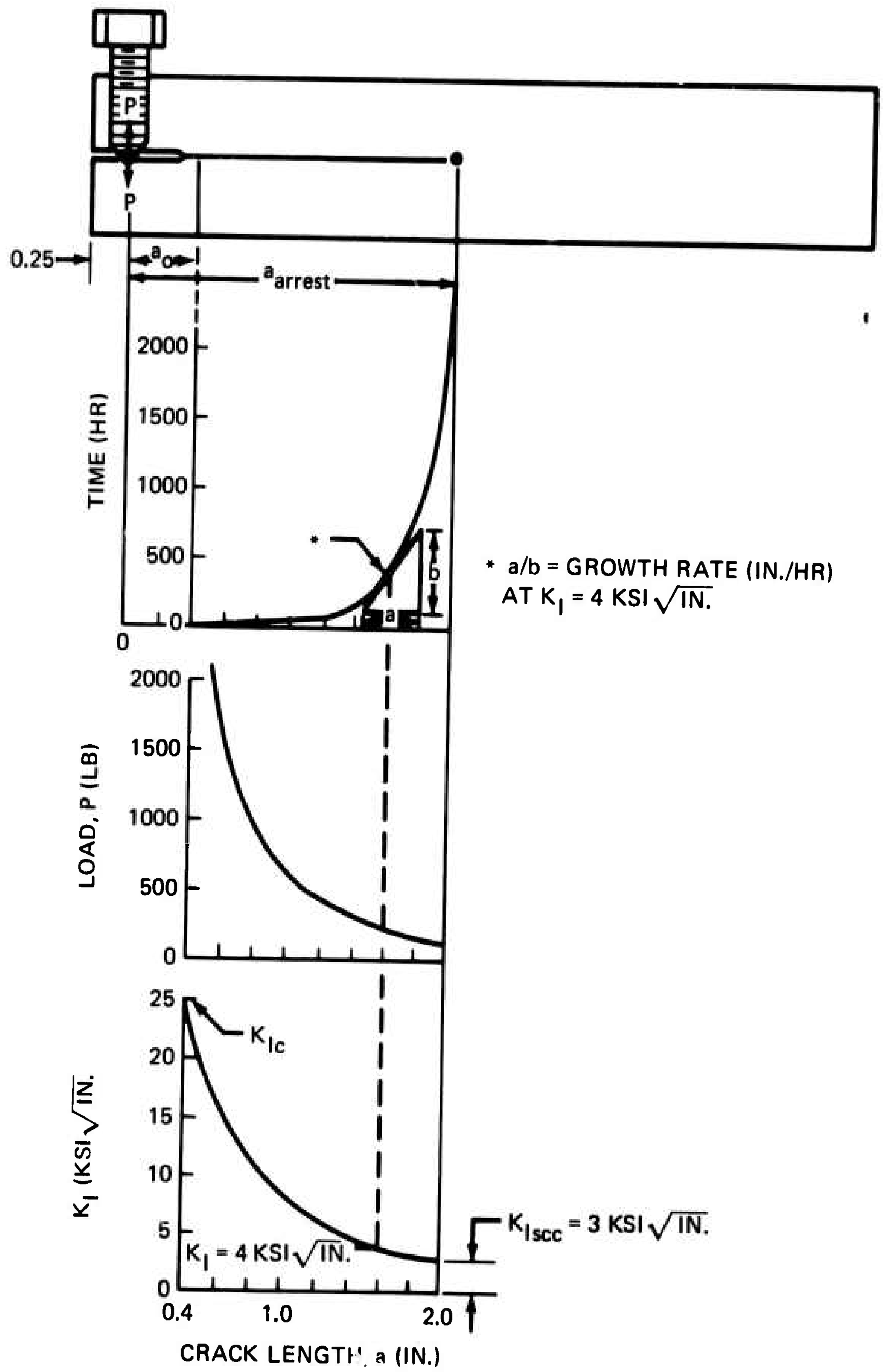


Figure 27. Effect of Crack Growth on Load and Stress Intensity under Constant Crack Opening Displacement Conditions (v = 0.010 Inch) in a 1- by 1- by 5-Inch Aluminum-Alloy DCB Specimen (From Ref. 26)

After the crack has been advanced about 0.1 in. beyond the end of the machined notch by bolt loading, the bolt end of the specimen is masked with a vinyl coating to prevent any galvanic action. The specimen is then placed in the test environment. The environment used in this study consisted of the intermittent application of several drops of a 3.5% NaCl solution to the machined notch of the specimen. The notch serves as the reservoir for the NaCl solution, which is applied three times each working day at 4- hr intervals. Crack length and time are monitored and a curve of crack length versus time is prepared. The slopes of the curve at different crack lengths provide crack growth rate data as a function of K_I. The crack length at which growth ceases (if this occurs) is then used to calculate K_{Iscc}. The procedure is illustrated schematically in Fig. 27. The bolt loaded DCB specimen and the outlined test technique have been used by one of the authors in a number of studies on stress-corrosion cracking in high-strength aluminum alloys (26, 27, 28, 29, 30, 31).

A summary of the crack growth rate data obtained for several aluminum alloys using this specimen (26) is shown in Fig. 28. Note the exceptionally rapid growth rates for 7079-T651 at the higher K_I levels. The outstanding attribute of this technique is simplicity. All that is needed are the DCB specimen, a bolt, a wrench, calipers to measure deflection, and a scale and hand lens to measure crack lengths.

The K_I-rate data for the different quench rates and aging treatments for alloy 21 are shown in Figs. 29, 30, 31, and 32 Generally, as aging time at 325°F or 350°F increases, crack growth rates decrease.

For the specimens quenched in 140°F or 212°F water, the maximum stress-corrosion crack growth rates for each amount of overaging at 325°F and 350°F are plotted in Figs. 33 and 34. For comparison, the maximum growth rates obtained (from Ref. 26) for X7080-T7, 7178-T76, 7175-T736, AZ74.61, 7049-T73, and 7075-T73 are indicated along the ordinate. Based on the data in Fig. 33, an aging time of 35 hr at 325°F was selected for the second step of the two-step aging treatment for alloy 21. It was expected that this amount of overaging would give stress-corrosion resistance comparable to that of 7178-T76 and 7175-T736 and better than that of X7080-T7.

The alloy X7080-T7 is a low-copper, chromium-free alloy which in this regard is similar to alloy 21. It was considered essential to overage alloy 21 sufficiently to achieve a maximum stress-corrosion crack growth rate less than that of X7080-T7 because it is well known that low-copper-content alloys in general and the low-copper-content, chromium-free X7080-T7 in particular exhibit lower smooth-specimen threshold stresses in an industrial environment than in an alternate-immersion environment. For example, X7080-T7 has a smooth-specimen threshold stress of 25 ksi in an alternate-immersion environment, but of only 15 ksi in an inland industrial atmosphere (6). Even 7075 in the susceptible T6 temper has a short-transverse threshold stress of as much as 14 ksi in an inland industrial atmosphere (32). Thus, to avoid, if possible, a low smooth-specimen threshold stress in industrial environments, alloy 21 was overaged enough to ensure a maximum crack growth rate lower than that of the chemically similar X7080-T7.

Selection of the 35 hr at 325°F treatment for the second step of the two-step aging treatment was made after only two weeks of testing. This amount of time was sufficient to allow stress-corrosion crack growth rates to be measured at the higher K_I levels for comp ri-

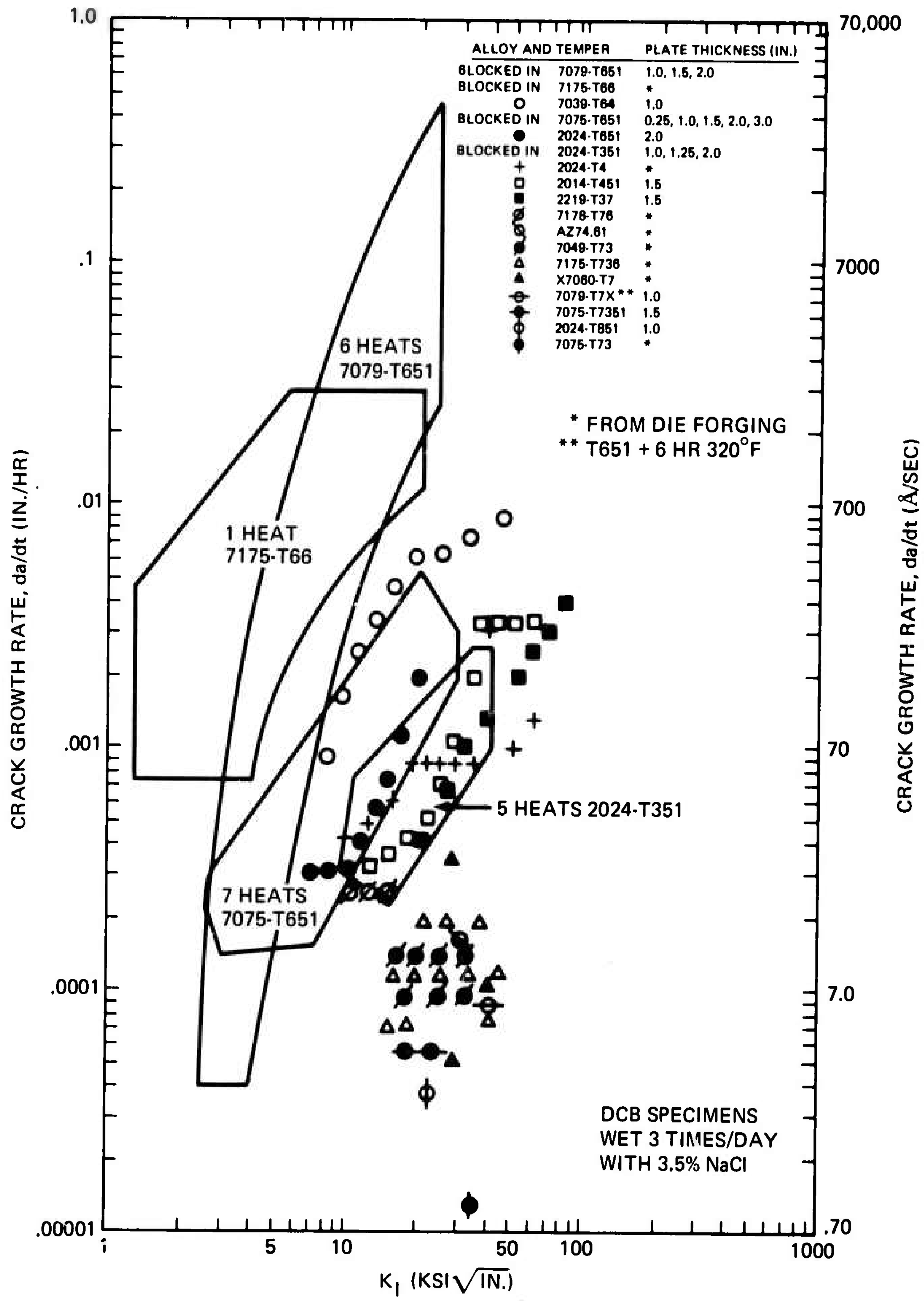


Figure 28. K_I-Rate Data from Short-Transverse DCB Specimens of Several Aluminum Alloys (From Ref. 26)

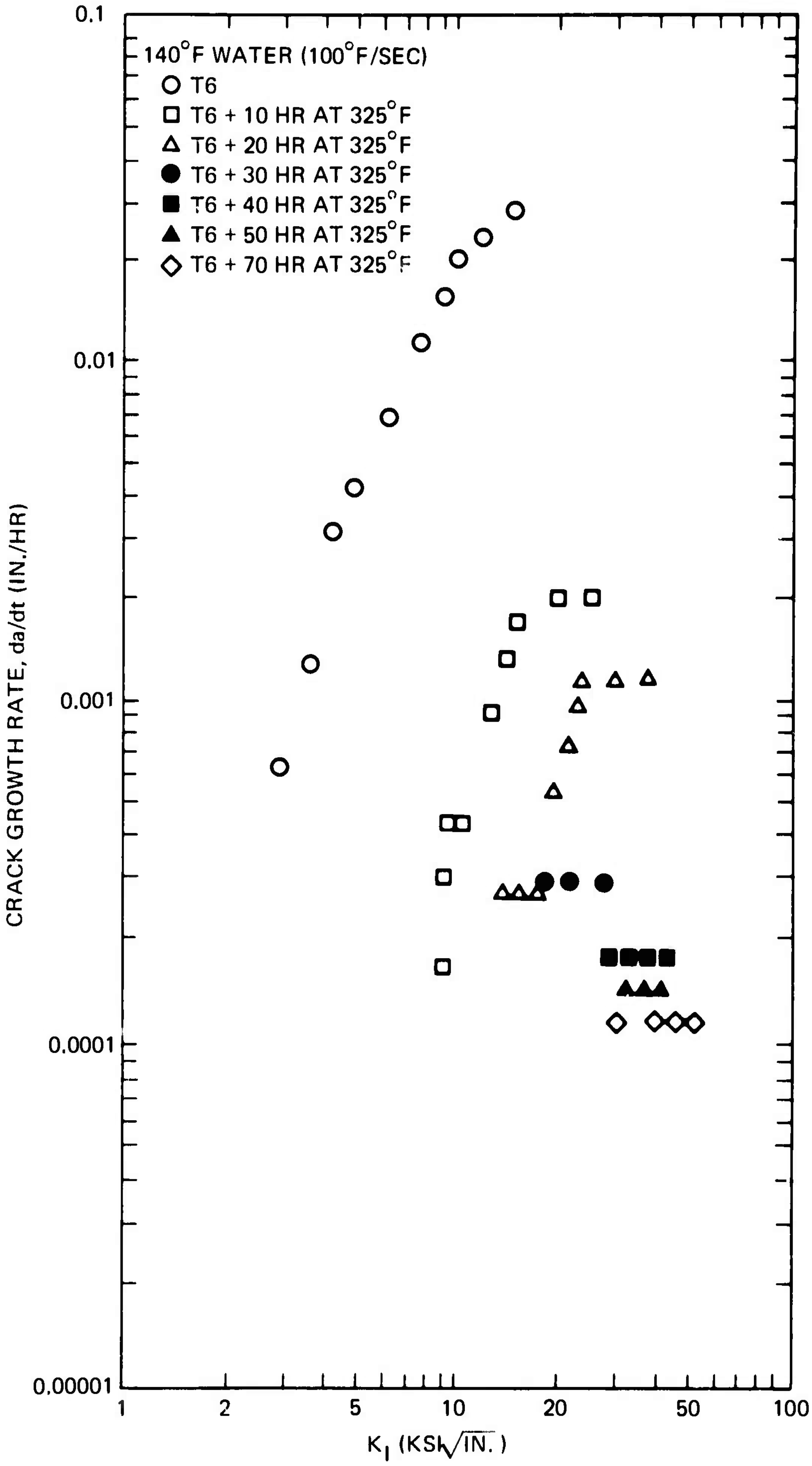


Figure 29. Effect of Heat Treatment on SCC Behavior of Alloy 21 Measured on Precracked DCB Specimens Intermittently Wetted with 3.5% NaCl. Specimens Were Quenched in 140°F Water.

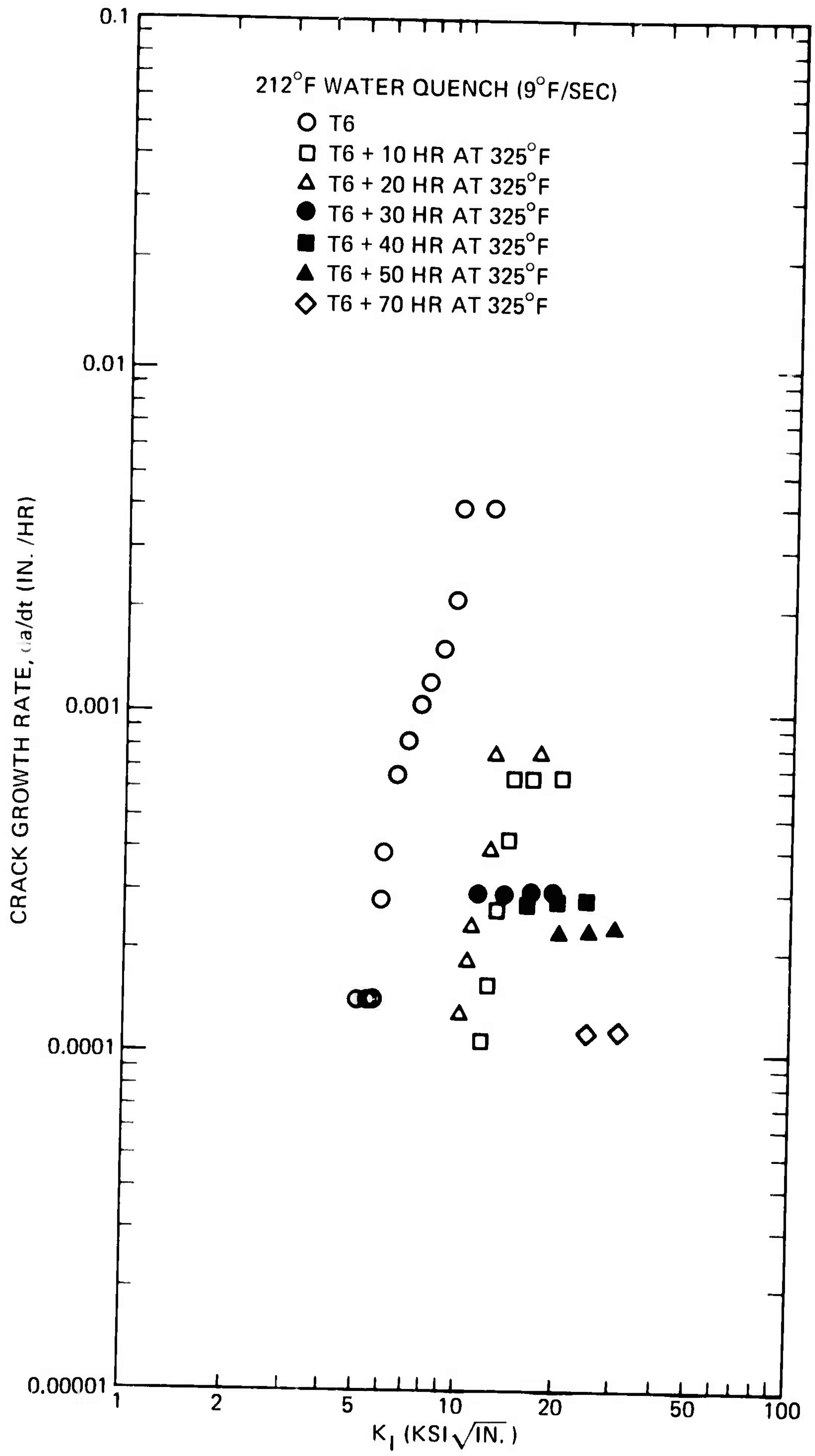


Figure 30. Effect of Heat Treatment on SCC Behavior of Alloy 21 Measured on Precracked DCB Specimens Intermittently Wetted with 3.5% NaCl. Specimens Were Quenched in Boiling Water.

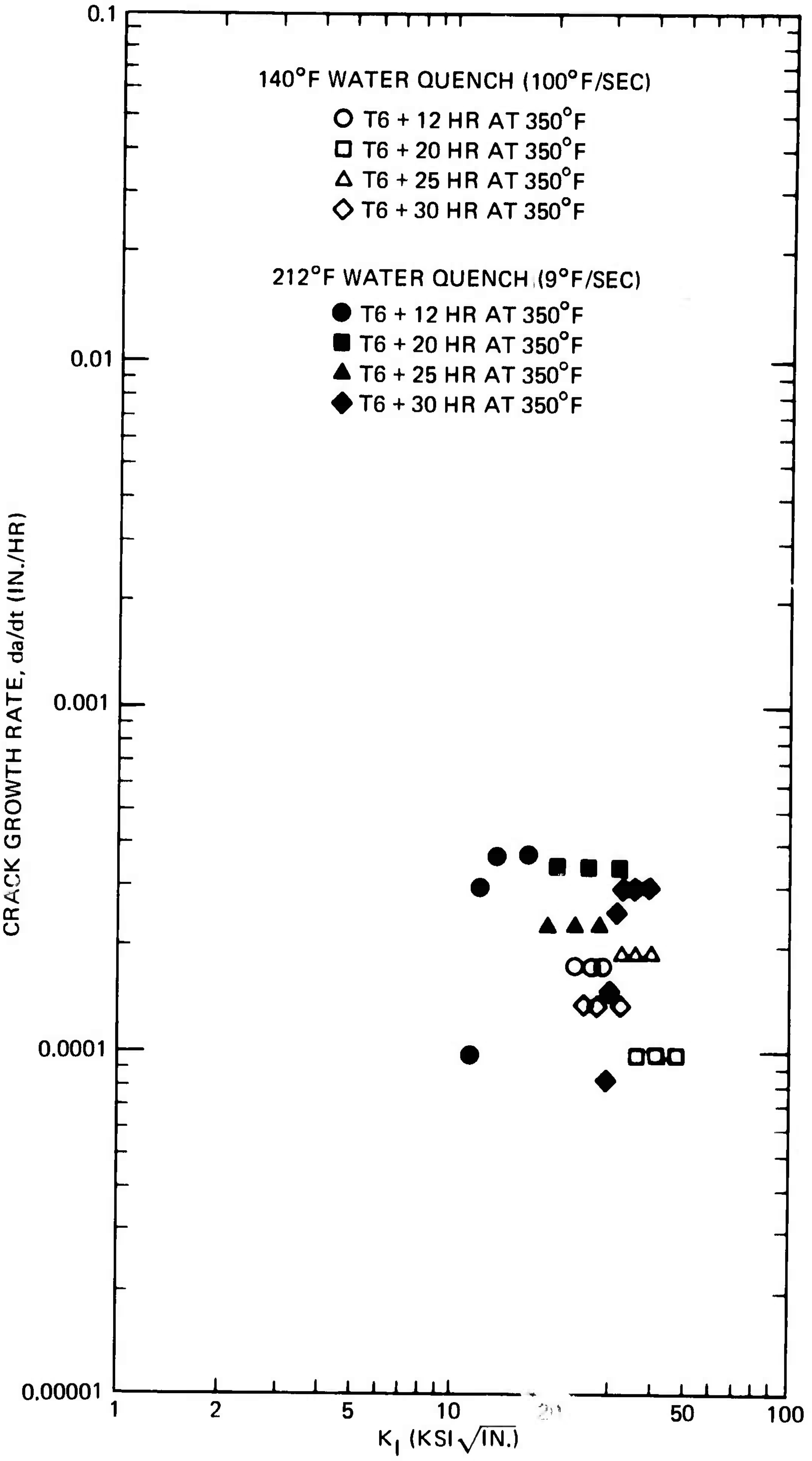


Figure 31. Effect of Heat Treatment and Quench Rate on SCC Behavior of Alloy 21 Measured on Precracked DCB Specimens Intermittently Wetted with 3.5% NaCl. Specimens Were Quenched in 140°F or 212°F Water.

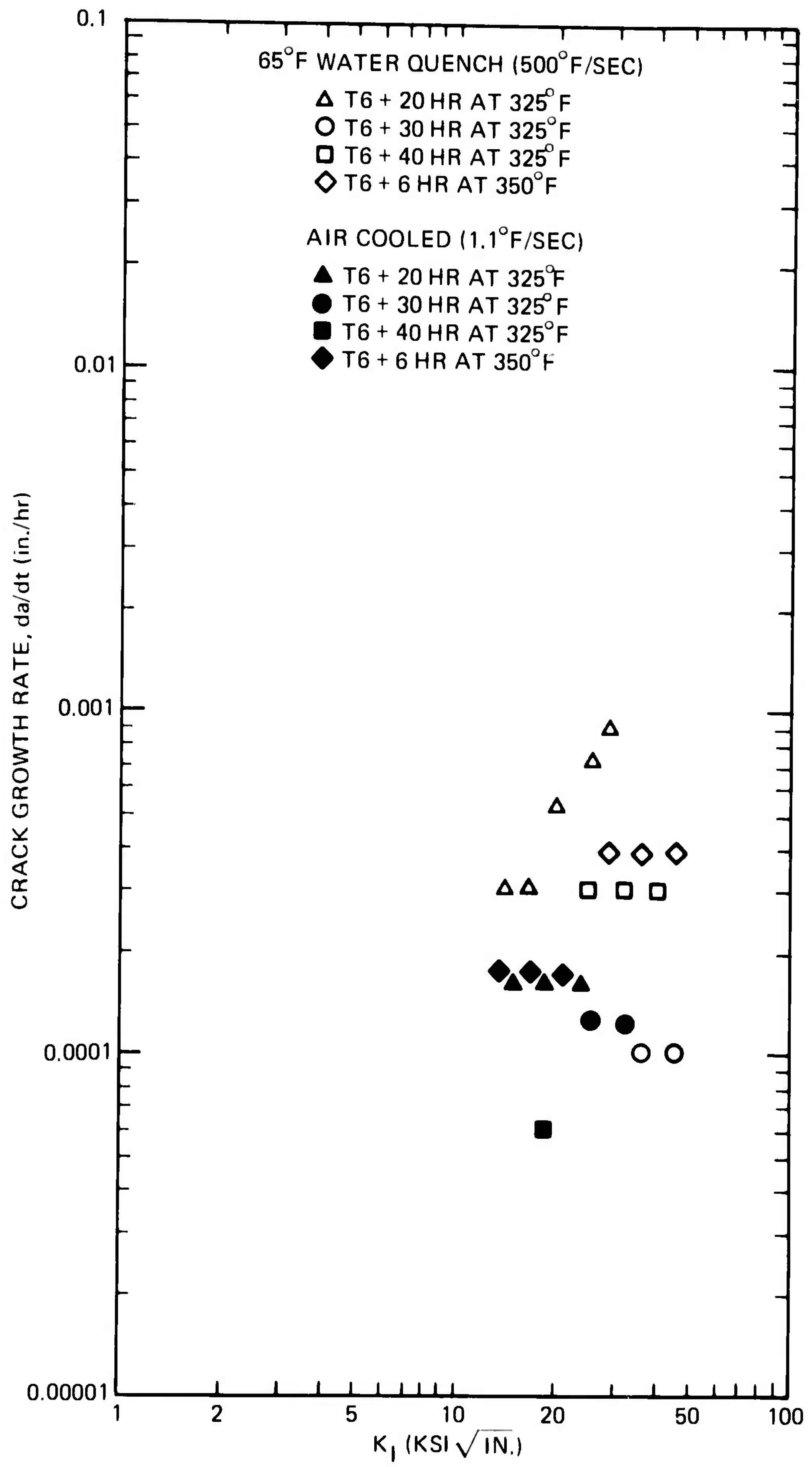


Figure 32. Effect of Heat Treatment on SCC Behavior of Alloy 21 Measured on Precracked DCB Specimens Intermittently Wetted with 3.5% NaCl. Specimens Were Quenched in 65°F Water or Air Cooled.

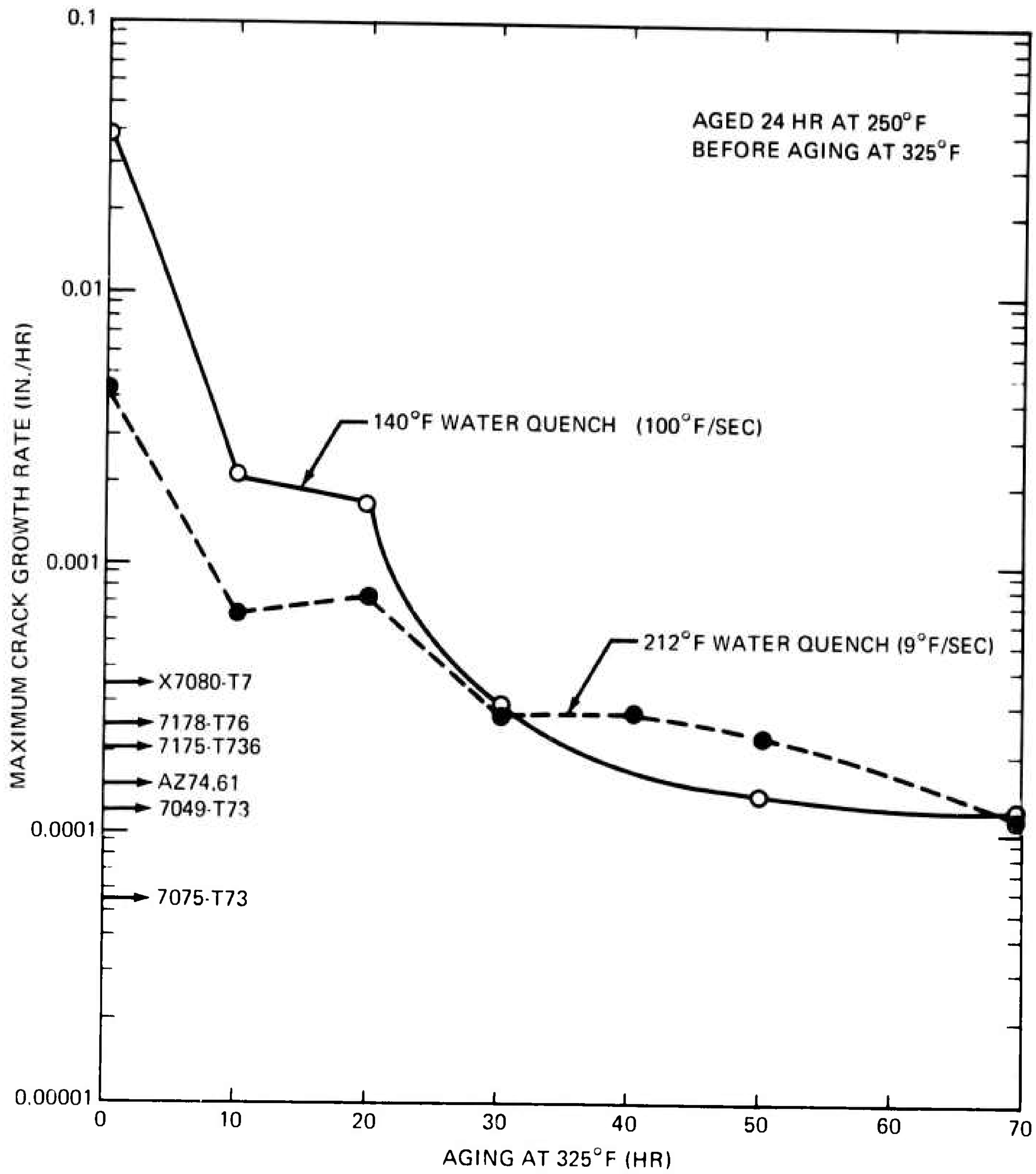


Figure 33 Effect of Aging Time at 325°F on the Maximum Stress-Corrosion Crack Growth Rates of Alloy 21. Maximum Crack Growth Rates for the Commercial Alloys Are from Ref. 26.

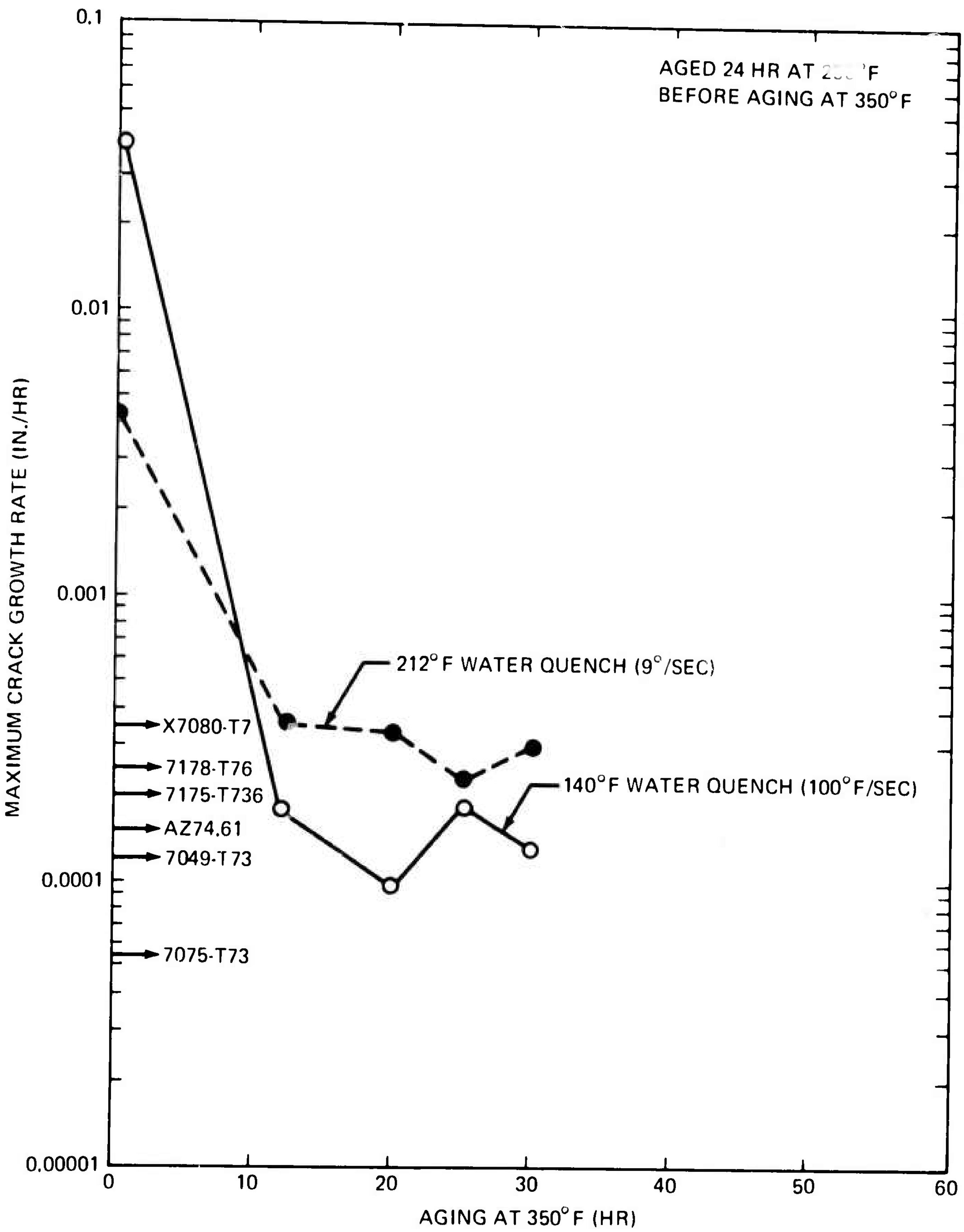


Figure 34. Effect of Aging Time at 350°F on the Maximum Stress-Corrosion Crack Growth Rates of Alloy 21. Maximum Crack Growth Rates for the Commercial Alloys Are from Ref. 26.

son with the commercial alloys, yet was significantly shorter than the normal 3-month waiting period for results from alternate-immersion, tension stress-corrosion tests.

At the conclusion of testing, the DCB stress-corrosion specimens were broken open by continued turning of the loading bolt. The fractured specimens are shown in Fig. 35. The specimens quenched in 140°F water and aged at 325°F show particularly well the decreasing extent of stress-corrosion crack penetration as overaging time at 325°F increased. The greater extent of crack front bowing in the more rapidly quenched specimens is also evident; the higher residual compressive stress on the surface of a rapidly quenched specimen causes a lower effective K_I level near the surface of the DCB specimen.

c. Effect of Quench Rate and Overaging Time on Smooth-Specimen Corrosion and Stress-Corrosion Properties

One-quarter-inch-diam. smooth stress-corrosion specimens were tested using deadweight loading in the standard 3.5% NaCl alternate-immersion environment. The specimen configuration is shown in Fig. 71, Appendix III, and the stress-corrosion apparatus is shown in Fig. 36. Specimens for testing were machined in the short-transverse direction from 3-in.-thick plate. They were machined from blanks quenched and heat treated as shown in the Phase II program outline (Fig. 20).

In addition, single specimens from the same blanks were exposed unstressed in the 3.5% NaCl alternate-immersion environment. The unstressed specimens were removed from test at the time of failure of the corresponding specimens stressed at 35 ksi. If no failure of the 35-ksi specimen occurred, both the stressed and unstressed specimens were removed from test after 90 days. The unstressed, corroded specimens and the unfailed stress-corrosion specimens were then tested in tension to determine residual ultimate strength and elongation.

Stress-corrosion results are shown in Figs. 37 and 38. Actual data are tabulated in Tables 27 and 28, Appendix II. Note that specimens quenched at the faster rate (140°F/sec) showed longer times to failure. For the 140°F water-quenched specimens, the data in Fig. 37 indicate that the threshold stress of 25 ksi could be achieved with the T6 + 20 hr at 325°F treatment. For the 212°F water-quenched specimens, the data in Fig. 38 indicate that the threshold stress goal of 25 ksi could not even be achieved with the T6 + 40 hr at 325°F treatment. However, conclusions based on time-to-failure data from smooth specimens can be meaningless, since specimens may fail from weakening by corrosion without any acceleration by stress. Figure 39 (from Ref. 33) illustrates the technique recommended for distinguishing stress-corrosion failure from mechanical failure. The results for the stressed and unstressed corrosion specimens of alloy 21 are shown in Figs. 40 and 41. (Data for the unstressed corrosion specimens are listed in Table 29, Appendix II.)

Note that at both quench rates and for almost all heat treatments, there was a large and fairly constant decrease in the residual strength of the stress-corrosion specimens tested at 35 ksi compared with the residual strength of the unstressed, corroded specimens. For the single stress-corrosion specimen treated at T6 + 40 hr at 325°F and tested at 25 ksi (Fig. 40), the residual strength was only slightly less than that of the unstressed companion specimen. These data would indicate that alloy 21 is fairly susceptible to stress-corrosion

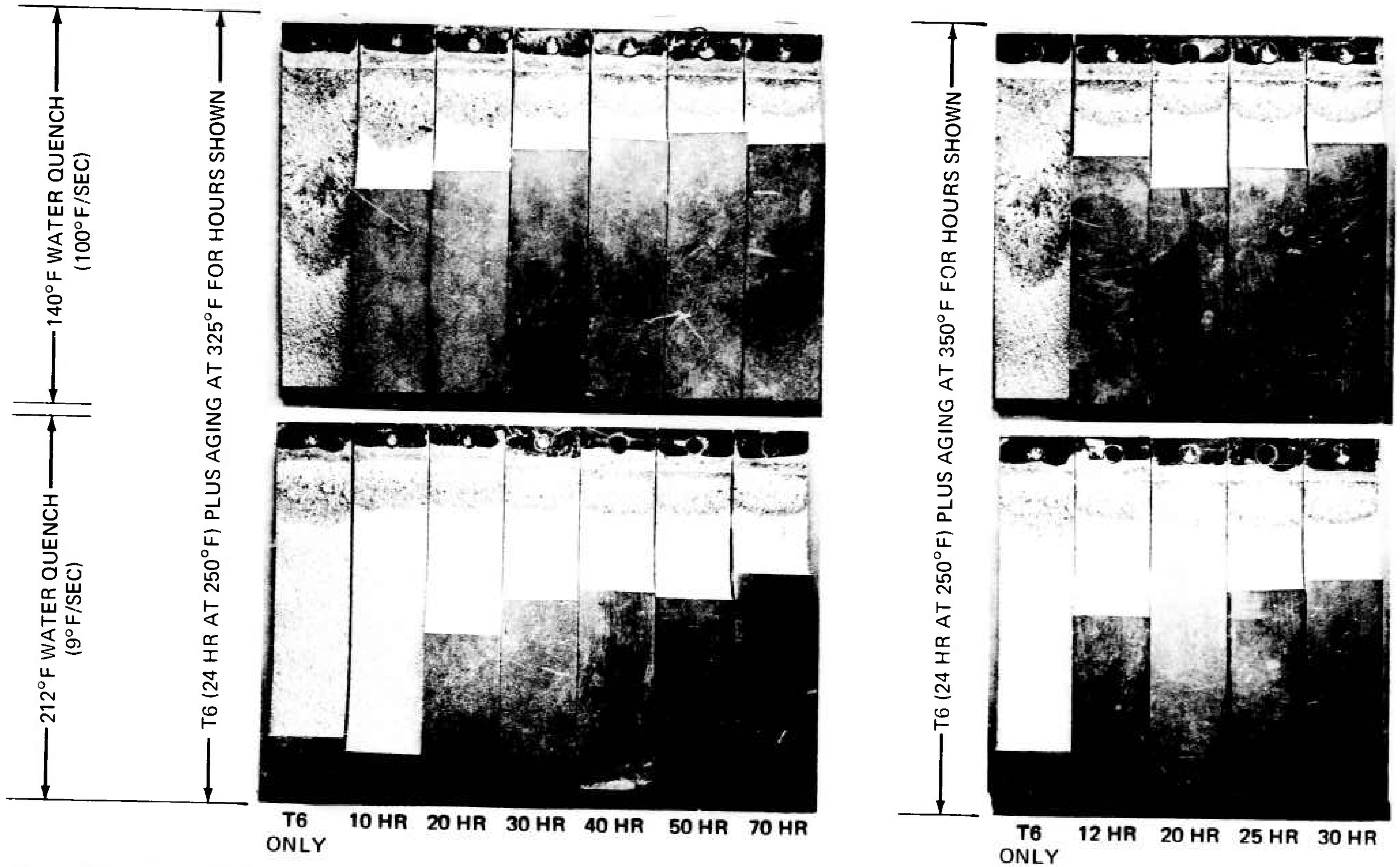


Figure 35. *Phase II Double Cantilever Beam Specimens after Being Broken Open at the Completion of Testing. The Darker Areas Show the Extent of Stress-Corrosion Crack Growth; the Lighter Areas Resulted from Rapid Fracture When the Specimens Were Broken Open. The Initial Pop-in Crack is Clearly Visible on Only a Few of the Specimens. Note the Greater Extent of Crack Growth and Crack Front Bowing on the More Rapidly Quenched Specimens (0.5X).*

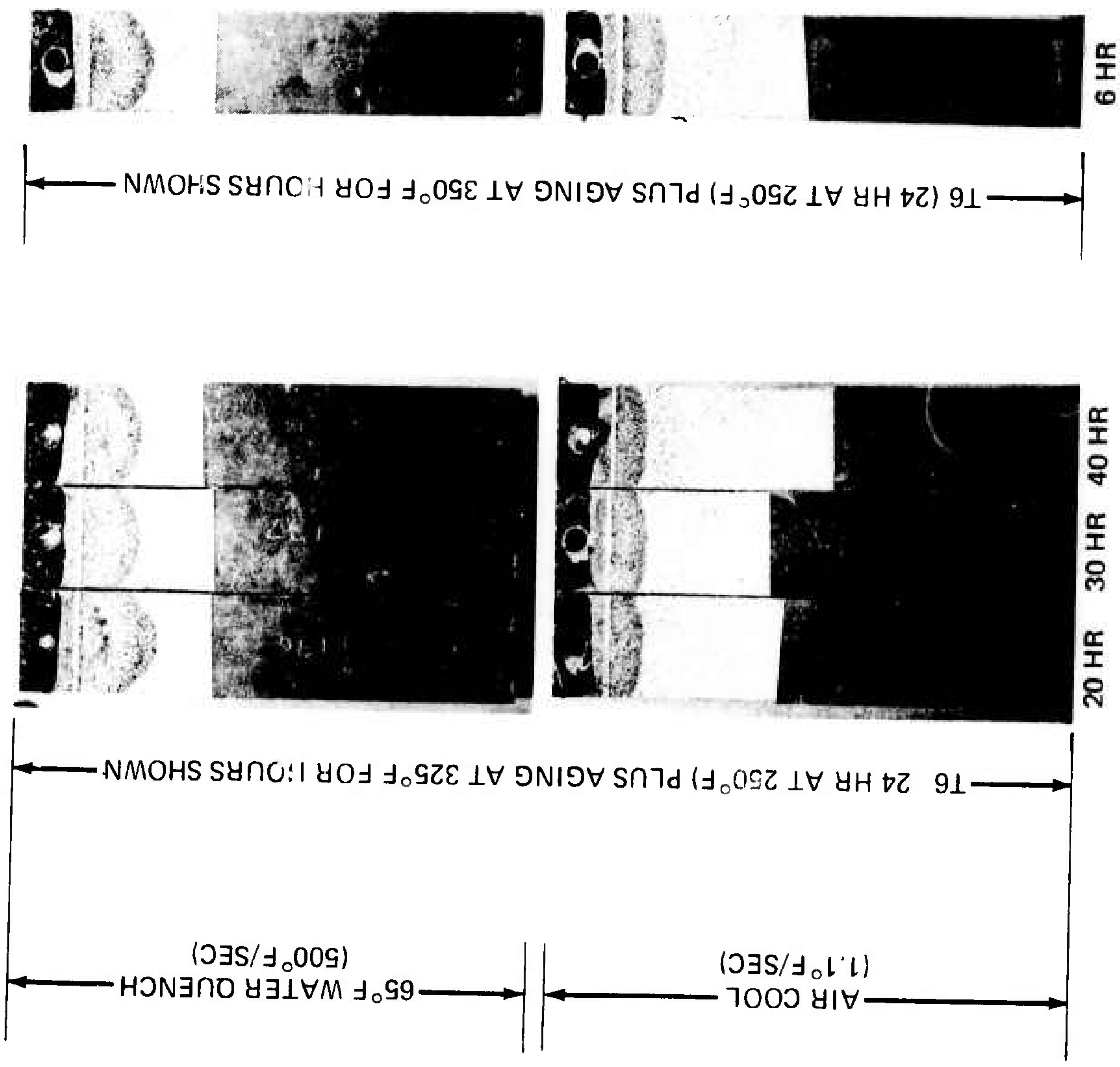


Figure 35.—Concluded

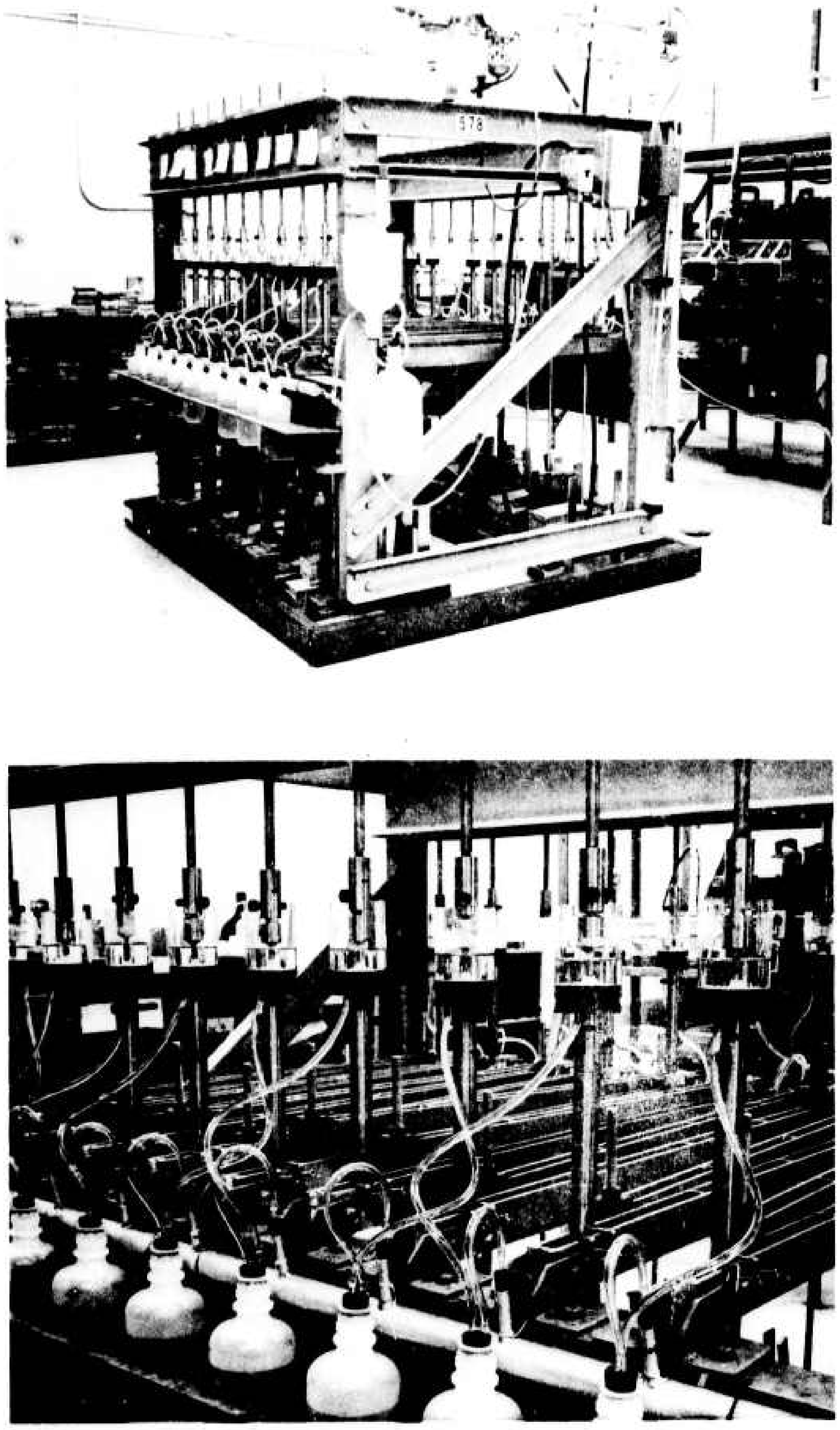


Figure 36. Deadweight Loading, Alternate-Immersion Stress-Corrosion Testing Facility. Nineteen Individual Test Cells Are Available.

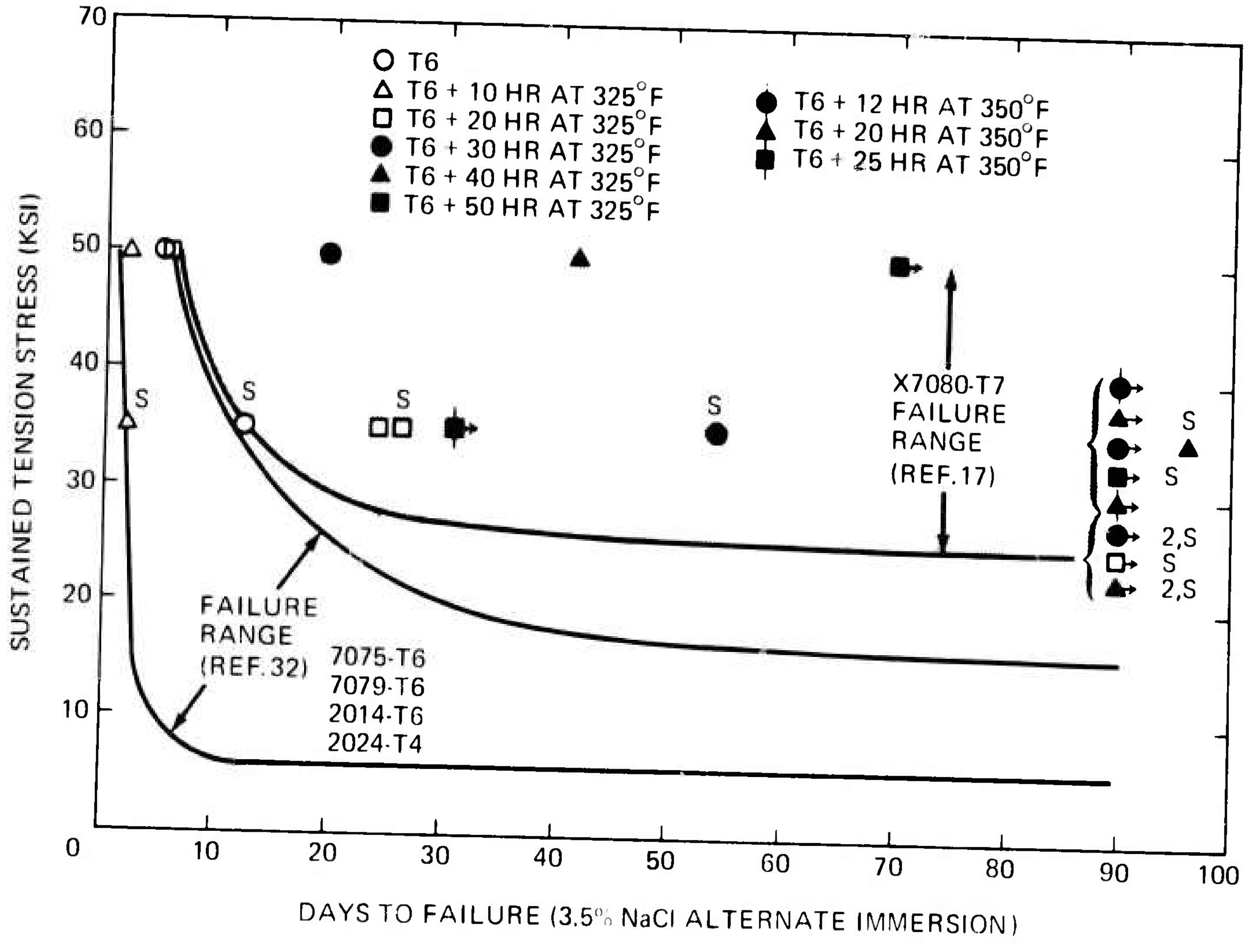


Figure 37. Short-Transverse Stress-Corrosion Data for Variously Overaged Alloy 21 Specimens and Several Commercial Alloys. Alloy 21 Specimen Blanks Were Quenched in 140°F Water (100°F/Sec).

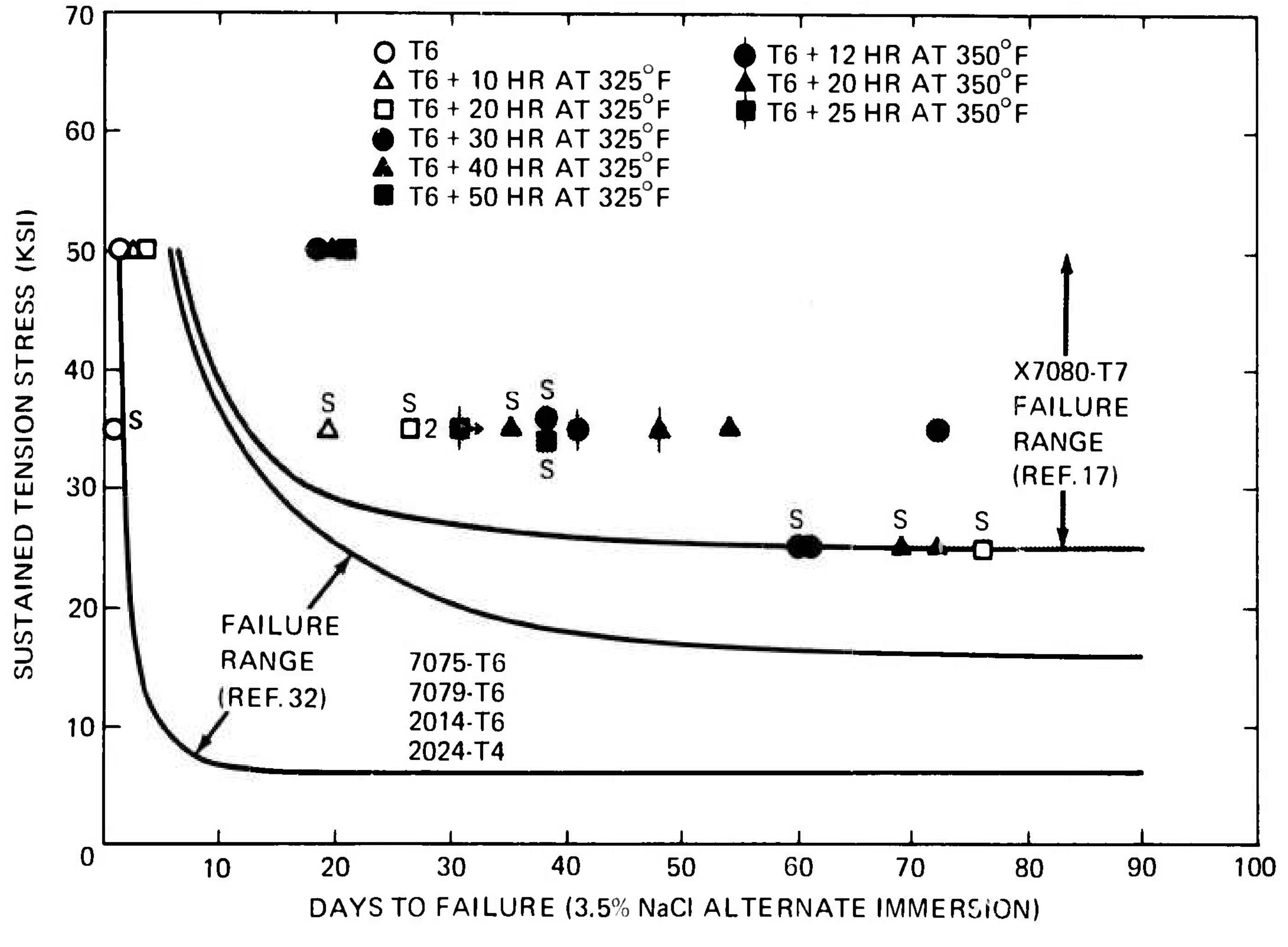


Figure 38. Short-Transverse Stress-Corrosion Data for Variously Overaged Alloy 21 Specimens and Several Commercial Alloys. Alloy 21 Specimen Blanks Were Quenched in 212°F Water (9°F/Sec).

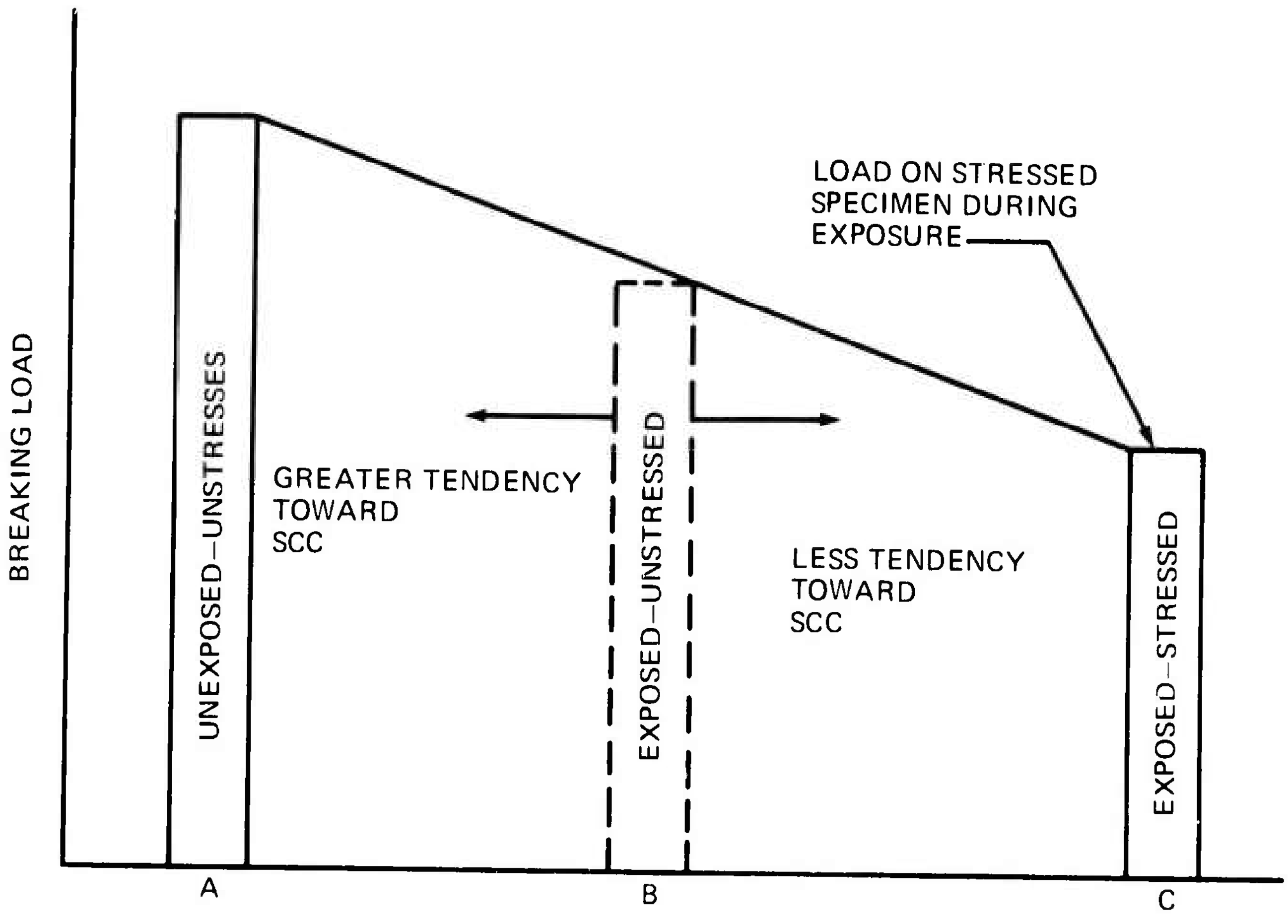


Figure 39. Distinguishing Stress-Corrosion Failure from Mechanical Failure (From Ref. 33)

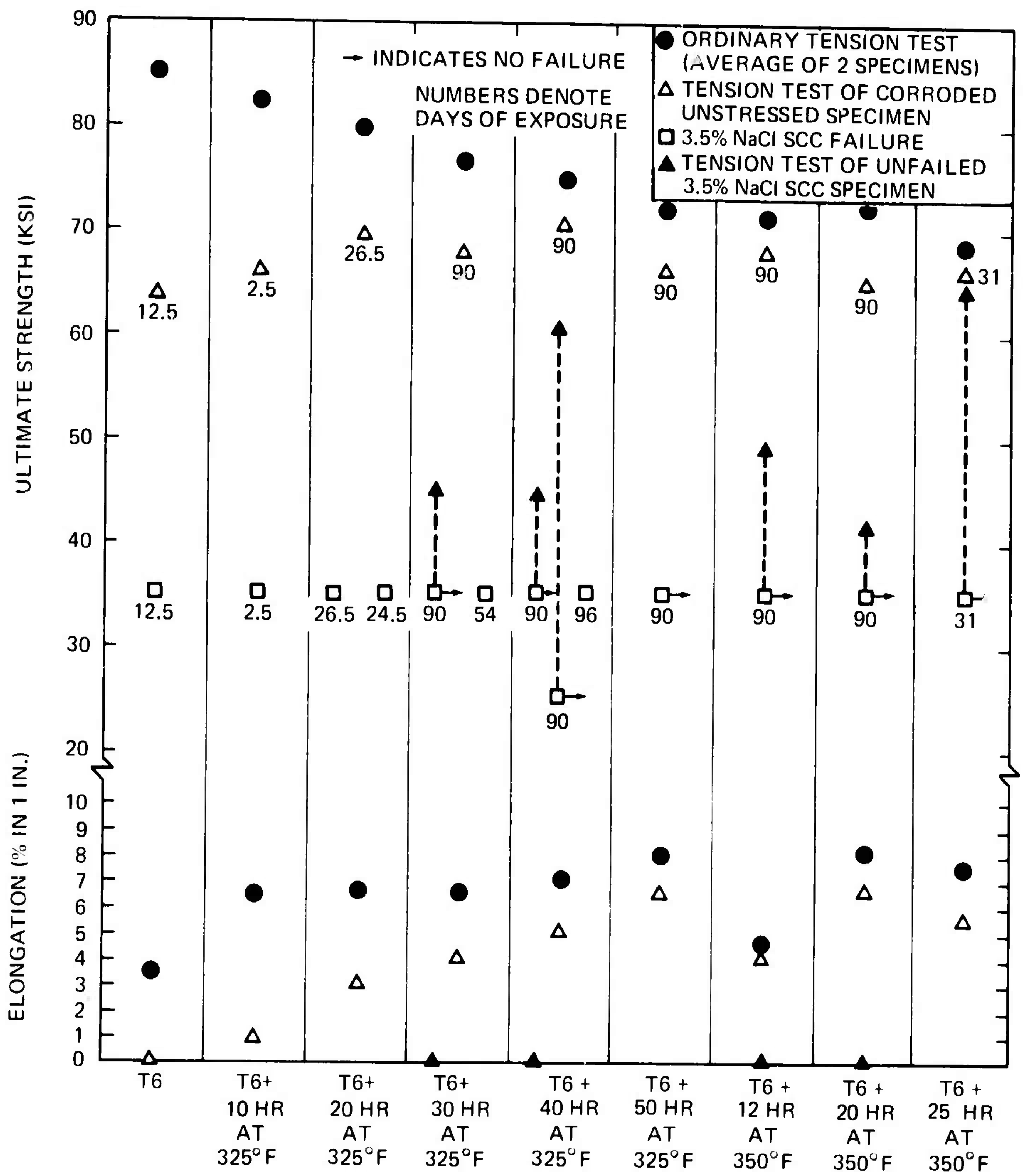


Figure 40. Effect of Corrosion and Stress-Accelerated Corrosion on Mechanical Properties of Alloy 21 in Various Heat-Treatment Conditions. Specimen Blanks Were Quenched in 140°F Water.

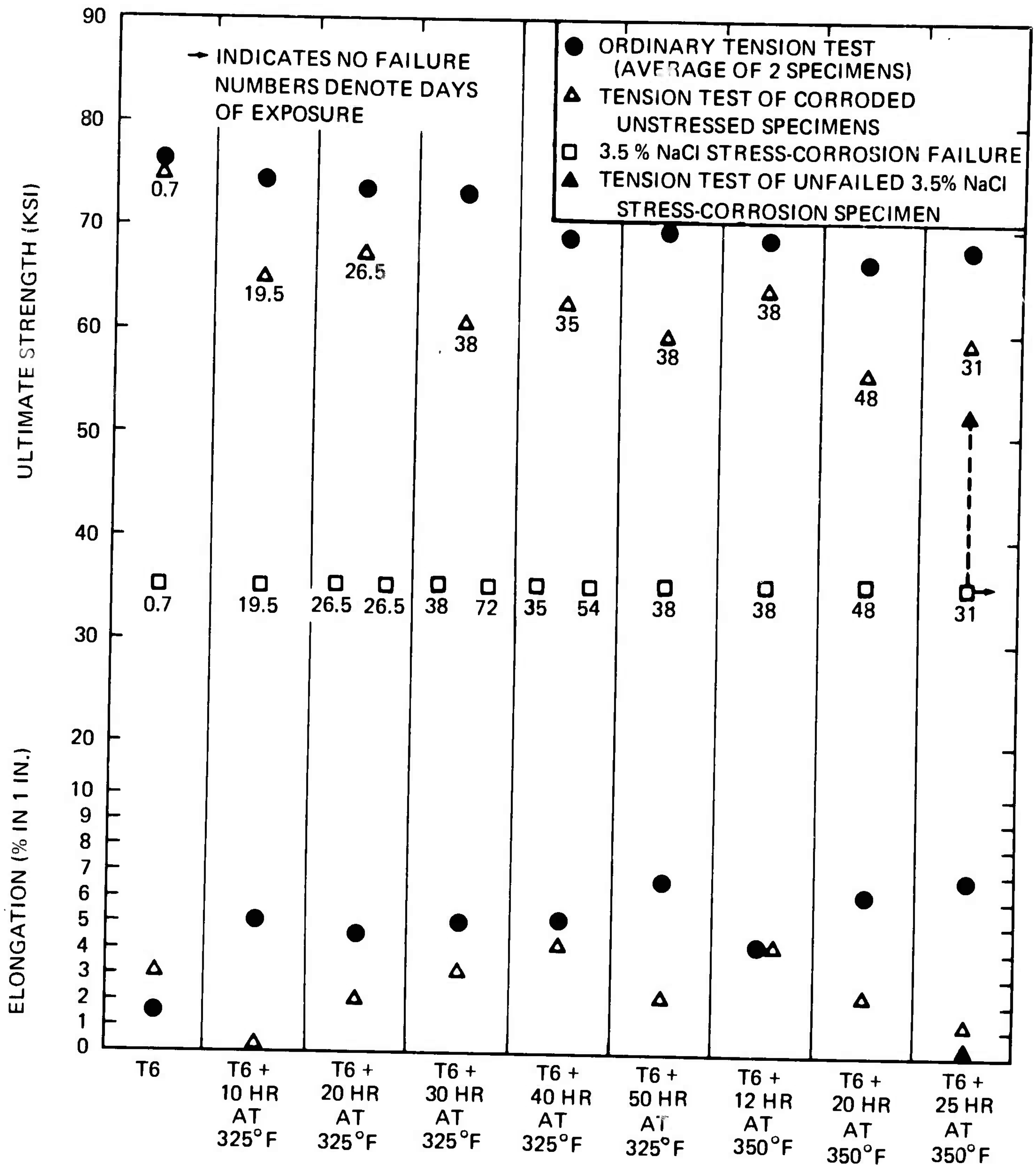


Figure 41. Effect of Corrosion and Stress-Accelerated Corrosion on Mechanical Properties of Alloy 21 in Various Heat-Treatment Conditions. Specimen Blanks Were Quenched in 212°F Water.

cracking at 35 ksi, even after 50 hr of overaging at 325°F. However, without further metallographic examination it cannot be concluded whether the loss of strength of the stressed specimens was due to deep pitting corrosion or to incipient stress-corrosion cracking. Therefore, to obtain a clear picture of the relative susceptibilities of alloy 21 after the various quench rates and overaging treatments, a metallographic examination was made on several specimens tested at 25 and at 35 ksi. Those specimens sectioned for this study are indicated by an "S" in Figs. 37 and 38.

d. Metallographic Study of Smooth Stress-Corrosion Specimens

The results of the metallographic examination of specimens quenched in 140°F water (100°F/sec) and tested at 25 and 35 ksi are shown in Figs. 42 and 43. Figure 42 and 43 indicate that the elimination of sharp intergranular attack on specimens tested at 25 and 35 ksi occurs somewhere between 30 and 40 hr of overaging at 325°F.

Results of the metallographic examination of specimens quenched in 212°F water (9°F/sec) and tested at 25 and 35 ksi are shown in Figs. 44 and 45. Again, it is indicated that the elimination of sharp intergranular attack on specimens tested at 25 and 35 ksi occurs between 30 and 40 hr of overaging at 325°F. Based on this metallographic evidence, the T6 + 35 hr at 325°F treatment selected for alloy 21 on the basis of crack growth rate data from DCB specimens appears to have been a good choice.

Figures 42 through 45 also indicate that for the T6 + 35 hr at 325°F treatment, the stress-corrosion threshold is near 35 ksi for specimens tested in the alternate-immersion environment. This is particularly important since, to give some assurance that threshold level in an industrial environment would meet the 25-ksi goal, it was desirable that alloy 21 show little evidence of sharp intergranular attack at 35 ksi in an alternate-immersion environment. The reasoning was the same as that discussed earlier and was based on the fact that the low-copper-content alloys in general and the low-copper-content, chromium-free X7080-T7 alloy in particular exhibit lower threshold stresses in an industrial environment than in an alternate-immersion environment. And alloy 21 is a low-copper, chromium-free alloy. In any case, by the time the smooth-specimen stress-corrosion data had been obtained, the remaining wrought products of alloy 21 had already been heat treated to the T6 + 35 hr at 325°F temper based on the earlier crack growth rate results.

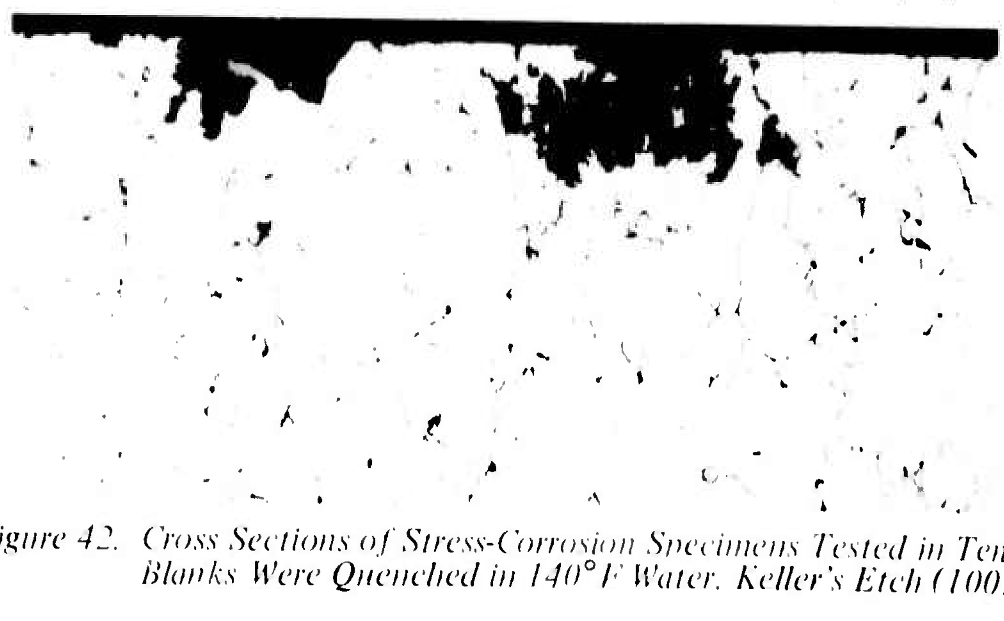
e. Heat Treatment of Wrought Products of Alloy 21

Alloy 21 wroughts products (die and hand forgings, plate, and extrusions) were heat treated in Boeing production facilities to simulate commercial heat treatment. The proc' ucts were solution treated in a gas-fired, vertical drop Despatch furnace that was 6 ft wide, 12 ft high, and 60 ft long (interior dimensions). The water quench bath below was 20 ft deep. Aging was performed in a front-loaded, 4- by 5- by 6-ft electric Coates furnace

The heat treating was accomplished in two loads. All forgings, plate, and heavy extrusions were heat treated in one load, and the square and angular cross-section extrusions were heat treated in another. The racking of parts for solution treatment was chosen to minimize distortion during quenching.

SPECIMEN 10C
T6 + 20 HR AT 325°F
REMOVED UNFAILED
AFTER 90 DAYS

SPECIMEN 12A
T6 + 30 HR AT 325°F
REMOVED UNFAILED
AFTER 90 DAYS



SPECIMEN 18C
T6 + 40 HR AT 325°F
REMOVED UNFAILED
AFTER 90 DAYS

Figure 42. Cross Sections of Stress-Corrosion Specimens Tested in Tension at 25 KSI. Specimen Blanks Were Quenched in 140°F Water. Keller's Etch (100X).

SPECIMEN 6B
T6
12.5 DAYS TO FAILURE

SPECIMEN 8B
T6 + 10 HR AT 325°F
2.5 DAYS TO FAILURE

SPECIMEN10B
T6 + 20 HR AT 325°F
26.5 DAYS TO FAILURE

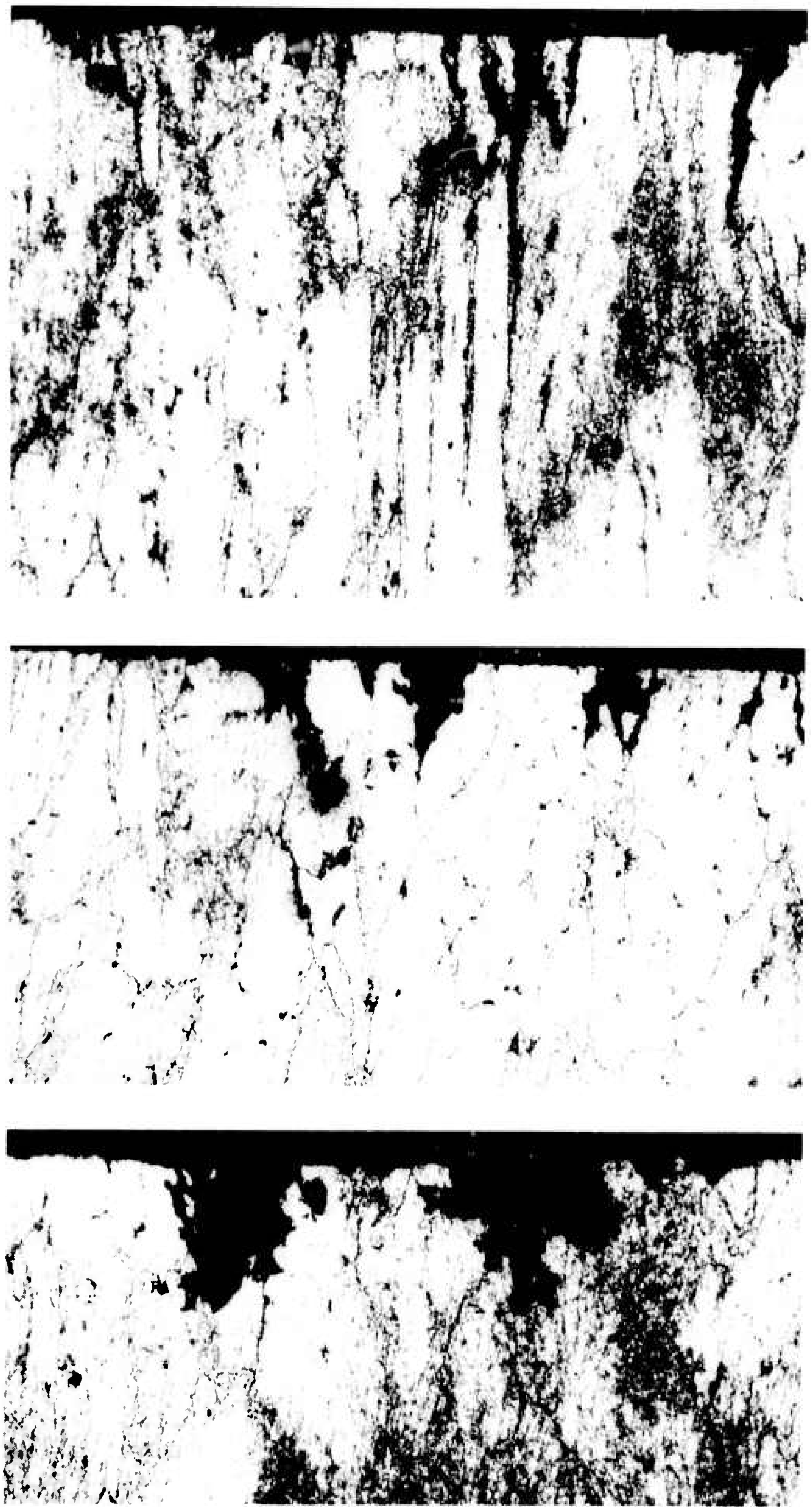
Figure 43. Cross Sections of Stress-Corrosion Specimens Tested in Tension at 35 KSI. Specimen Blanks Were Quenched in 140°F Water. Keller's Etch (100X).

SPECIMEN 11B
T6 + 30 HR AT 325°F
54 DAYS TO FAILURE

SPECIMEN 17B
T6 + 40 HR AT 325°F
96 DAYS TO FAILURE

SPECIMEN 20B
T6 + 50 HR AT 325°F
REMOVED UNFAILED
AFTER 90 DAYS

Figure 43—Concluded

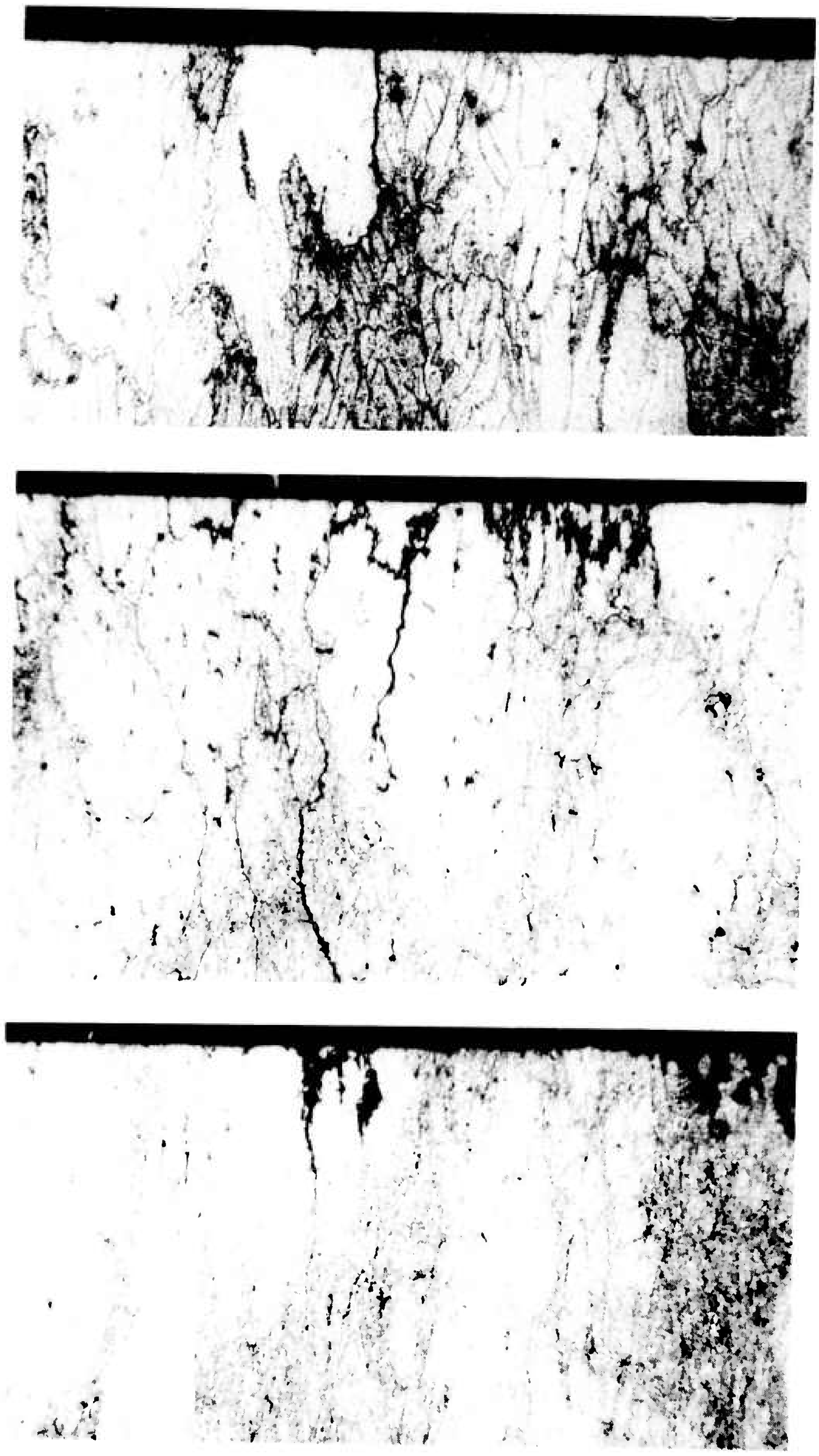


SPECIMEN 36C
T6 + 20 HR AT 325°F
76 DAYS TO FAILURE

SPECIMEN 38C
T6 + 30 HR AT 325°F
60 DAYS TO FAILURE

SPECIMEN 40A
T6 + 40 HR AT 325°F
69 DAYS TO FAILURE

Figure 44. Cross Sections of Stress-Corrosion Specimens Tested in Tension at 25 KSI. Specimen Blanks Were Quenched in 212°F Water. Keller's Etch (100X).



SPECIMEN 32B
T6
0.7 DAYS TO FAILURE

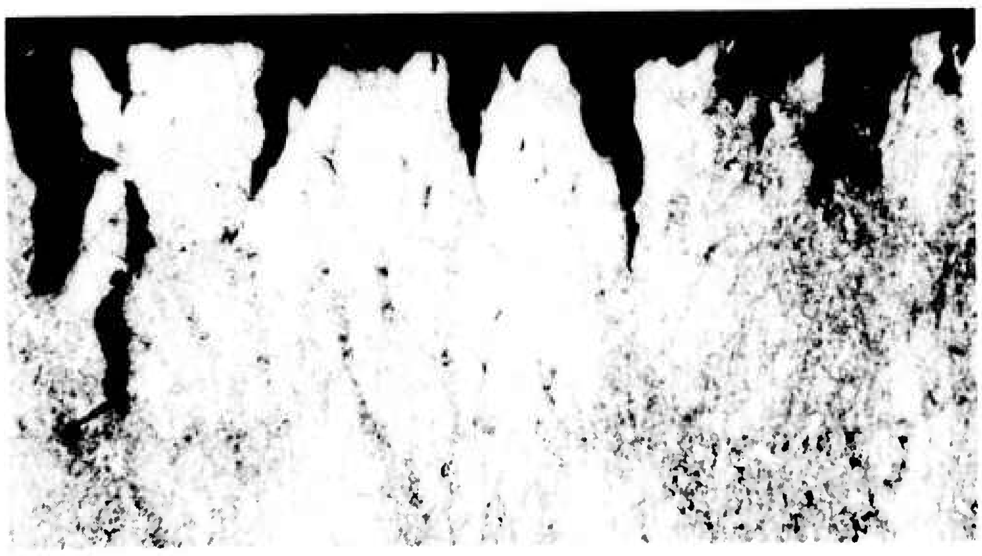
SPECIMEN 34B
T6 + 10 HR AT 325°F
19.5 DAYS TO FAILURE

SPECIMEN 36B
T6 + 20 HR AT 325°F
26.5 DAYS TO FAILURE

Figure 45. Cross Sections of Stress-Corrosion Specimens Tested in Tension at 35 KSI. Specimen Blanks Were Quenched in 212°F Water. Keller's Etch (100X).

SPECIMEN 38B
T6 + 30 HR AT 325°F
38 DAYS TO FAILURE

SPECIMEN 40B
T6 + 40 HR AT 325°F
35 DAYS TO FAILURE



SPECIMEN 42B
T6 + 50 HR AT 325°F
38 DAYS TO FAILURE

Figure 45. Concluded

In the first load, the landing gear die forgings were placed vertically with the heavy end down, the plate was racked vertically, and all hand forgings were laid flat. Prior to heat treating, part of a 6-in.-thick hand forging was cut up into 3-in.- and 1-in-thick slices. The heat-treatment sequence was as follows: solution treat at 870° ± 3°F for 7 hr, quench in 75°F water with a quench delay of 10 sec and a room-temperature delay time of 1 hr before artificial aging. Aging was performed at 250° ± 3°F for 24 hr and 325° ± 3° F for 35 hr. The furnace heatup rate was 35°F/hr from room temperature to 250°F and from 250°F to 325°F. Heatup was accomplished by increasing the temperature setting 17° to 18°F every half hour.

In the second load, the small cross-section extrusions were racked vertically. The heat-treatment procedure for this load was essentially the same as for the first load except that the solution treatment time was 1 hr and 35 min.

SECTION IV

PHASE III. CHARACTERIZATION OF WROUGHT PRODUCTS OF ALLOY 21

1. PHASE III TEST PROGRAM OUTLINE

After heat treatment of the wrought products, specimens for the Phase III characterization study were machined from each part. Specimens were taken from both the surface and center of the thicker materials. They were obtained for evaluation of mechanical, fatigue, fracture, stress-corrosion, and exfoliation corrosion properties as described in the Phase III test program outlined in Table 5. The specimen configurations used during this characterization study are shown in Figs. 71 through 81, Appendix III.

2. CONDUCTIVITY VALUES FOR WROUGHT PRODUCTS OF ALLOY 21

The ranges in electrical conductivity (% IACS) and in hardness (R_B) for specimen blanks machined from the various wrought products are given in Table 6. As noted earlier, conductivity values for alloy 21 were less than those for 7075-T73, even though alloy 21 had been aged at 325°F for times longer than encountered in achieving the T73 temper for 7075.

3. OPTICAL AND TRANSMISSION ELECTRON MICROSCOPY OF WROUGHT PRODUCTS OF ALLOY 21

The microstructures of the Phase III wrought products may be seen in Figs. 46 through 50. The microstructures were typical of wrought 7000 series alloys, and all products exhibited an unrecrystallized structure, with the exception of the surface layers on all extrusions, where the structure was completely recrystallized (Fig. 47). A recrystallized surface layer is typical of extruded products.

Transmission electron micrographs of material from the surface and center of the 6.75-in.-diam landing gear die forging are shown in Fig. 51. For comparison, a transmission electron micrograph of Kaiser's 7049-T73 alloy is shown in Fig. 52. Both alloys contain precipitate-free zones adjacent to grain boundaries, but any difference in the degree of overaging of the two alloys is not readily apparent. One difference that is apparent is the higher density of intermetallic particles in 7049-T73. Since 7049-T73 contains chromium (nominally 0.15%), these particles are probably E phase ($Al_{12}Mg_2Cr$). Alloy 21 does not contain chromium and showed a much lower density of this type of intermetallic particle.

4. MECHANICAL PROPERTIES OF WROUGHT PRODUCTS OF ALLOY 21

Averaged tension, compression, shear, and bearing results for wrought products of alloy 21 are given in Tables 7 through 14. Actual data are shown in Tables 30 through 41, Appendix III. As expected, ultimate and yield strengths for the extrusions were higher than for the forgings. For equal section thickness, the properties for die and hand forgings were very similar. Generally, surface property values were slightly higher than center property values. Except for the angular extrusions, all elongation results were above Federal

Table 5. Phase III Testing Program for Characterizing Wrought Products of Alloy 21

			DIE FORGINGS															
			Landing gear (6.75 in. diam x 33 in.)				Navajo (4 x 6 x 55 in.)											
			Ingot 21562			Ingot 21563[a]	Ingot 21562											
			Piece 271		Pc 272	Piece373	Piece 261					Piece 262					Piece 263	
			Heat-treat thickness (in.)				Heat-treat thickness (in.)					Heat-treat thickness (in.)						
			6.75				4		2.38	1.0	0.62	4		2.38	1.0	0.62	4	2.38
	Specimen type	Grain direction[d]	S[b]	C[b]		C[c]	S	C	S	C	C	S	C	S	C	C	C	S
Mechanical properties	Tension	L	3	3		2	1	1			1	1	1			1	2	
		ST	3	3		2		1,1(LT)			1(LT)		1,1(LT)			1(LT)		
	Compression	L	3	3				1					1					
		ST	3	3				1					1					
	Shear	L	2					1					1					
		ST	2					1					1					
	Bearing[e] E/D = 1.5	L	2	2														
		ST	2															
	E/D = 2.0	L	2	2														
		ST	2															
Fatigue properties	Smooth axial fatigue	L		6														
		ST		6														
	Notched axial fatigue	L		9														
		ST		9		6												
Fracture toughness properties	Notched bend	L		2		2				2								
		ST		2		2		1(LT)					1(LT)					
	Precracked charpy	L																
		ST																
Corrosion and stress-corrosion properties	3-in dead load type	ST	3	5														
	Stress frame type	ST	7	5		9			5									
	Battelle type	ST	9															
	DCB	ST	2															9
	Exfoliation corrosion	ST										1		1	1			1

Table 5.–Continued

	Specimen type	Grain direction[d]	EXTRUSIONS: 0.1" × 1.0" Angle, 20 pieces 72 in. long, 5 pieces 48 in. long; Ingot 21560; 0.1- x 0.1- x 72-In. angle	0.25" × 1.0" Angle, 14 pieces 72 in. long; Ingot 21560; 0.25-x 0.25-x72-In. angle	1.0" × 1.0" Bar, 6 pieces 72 in. long, 1 piece 48 in. long; Ingot 21565; 1- x 1- x 72-In. angle	6.0" × 2.0" Panel, 5 pieces 72 in. long, 2 pieces 48 in. long; Ingot 21565; 2- x 6- x 72-In. panel
			Heat-treat thickness (in.)			
			0.1	0.25	1.0	2.0
			C[b]	C	C	C
Mechanical properties	Tension	L	2	2	2	2
		ST				2
	Compression	L			2	2
		ST				
	Shear	L				
		ST				
	Bearing[e] E/D = 1.5	L				
		ST				
	E/D = 2.0	L				
		ST				
Fatigue properties	Smooth axial fatigue	L				
		ST				
	Notched axial fatigue	L				6
		ST				
Fracture toughness properties	Notched bend	L				2
		ST				
	Precracked charpy	L				
		ST				
Corrosion and stress-corrosion properties	3-in dead load type	ST				3
	Stress frame type	ST				6
	Battelle type	ST				
	DCB	ST			2	2
	Exfoliation corrosion	ST				

Table 5. Concluded

			HAND FORGINGS				PLATE
			6-x10-x45 in.			6x9.5x30 in.	2 pieces 3 x 20 x 43 in. 1 piece 3 x 18 x 18 in.
			Ingot 21562			Ingot 21563[a]	Ingot 21573
			Piece 251	Piece 251A	Piece 252	Piece 353	3 x 20 x 43 in. plate
			Heat-treat thickness (in.)				
	Specimen type	Grain direction[d]	6	3	1	6	3
			C[b]	C	C	C	C
Mechanical properties	Tension	L	3	3	3	2	2
		ST	3	3	3	2	2,2(LT)
	Compression	L	3	3	3		2
		ST	3	3	3		
	Shear	L	2	2	2		2
		ST	2	2	2		2
	Bearing[e] E/D = 1.5	L	2	2	2		
		ST	2	2	2		
	E/D = 2.0	L	2	2	2		
		ST	2	2	2		
Fatigue properties	Smooth axial fatigue	L					
		ST					
	Notched axial fatigue	L	9		9		
		ST	9		9		
Fracture toughness properties	Notched bend	L	2	2	2		2
		ST	2				2,2(LT)
	Precracked charpy	L					2
		ST					2,2(LT)
Corrosion and stress-corrosion properties	3-in dead load type	ST	9				5
	Stress frame type	ST			9		5
	Battelle type	ST					
	DCB	ST	2		2		10
	Exfoliation corrosion	ST					

a This ingot contains small inclusions.

b S or C denotes that specimen was taken near surface or center with respect to heat-treated thickness.

c These center specimens were taken from locations identical to those from Piece 271.

d Grain direction other than L and ST is indicated in parentheses after the number of specimens.

e E/D denotes edge margin to hole diameter ratio.

f Specimens were taken from one piece only.

Table 6. Hardness and Conductivity Ranges for Phase III Wrought Products of Alloy 21

Alloy product form	Overall dimensions (in.)	As-heat-treated thickness (in.)	Furnace load	Conductivity range in or near center of part (% IACS)	Hardness range in or near center of part (R_B)
Die forging (landing gear)	6.75 diam x 33	6.75		37.5–39.1	83.8–87.9
Die forging (Navajo type)	4 x 6 x 55	4		36.8–37.2	87.8–89.1
		1.5		36.9–37.6	
Hand forging	6 x 10 x 45	6	1	36.8–37.7	84.0–88.0
		3		36.9–37.3	84.2–88.0
		1		36.6–37.3	86.8–87.7
Plate	3 x 20 x 43	3		37.2–37.7	84.3–86.3
Extruded panel	2 x 6 x 38 ft	2		37.8–38.1	87.0–88.0
Extruded angle	0.1 x 0.1 x 140 ft	0.1		39.3–39.8	82.3–83.0
Extruded angle	0.25 x 0.25 x 84 ft	0.25	2	38.2–38.3	83.9–89.8
Extruded bar	1 x 1 x 40 ft	1		38.0–38.2	86.2–87.2

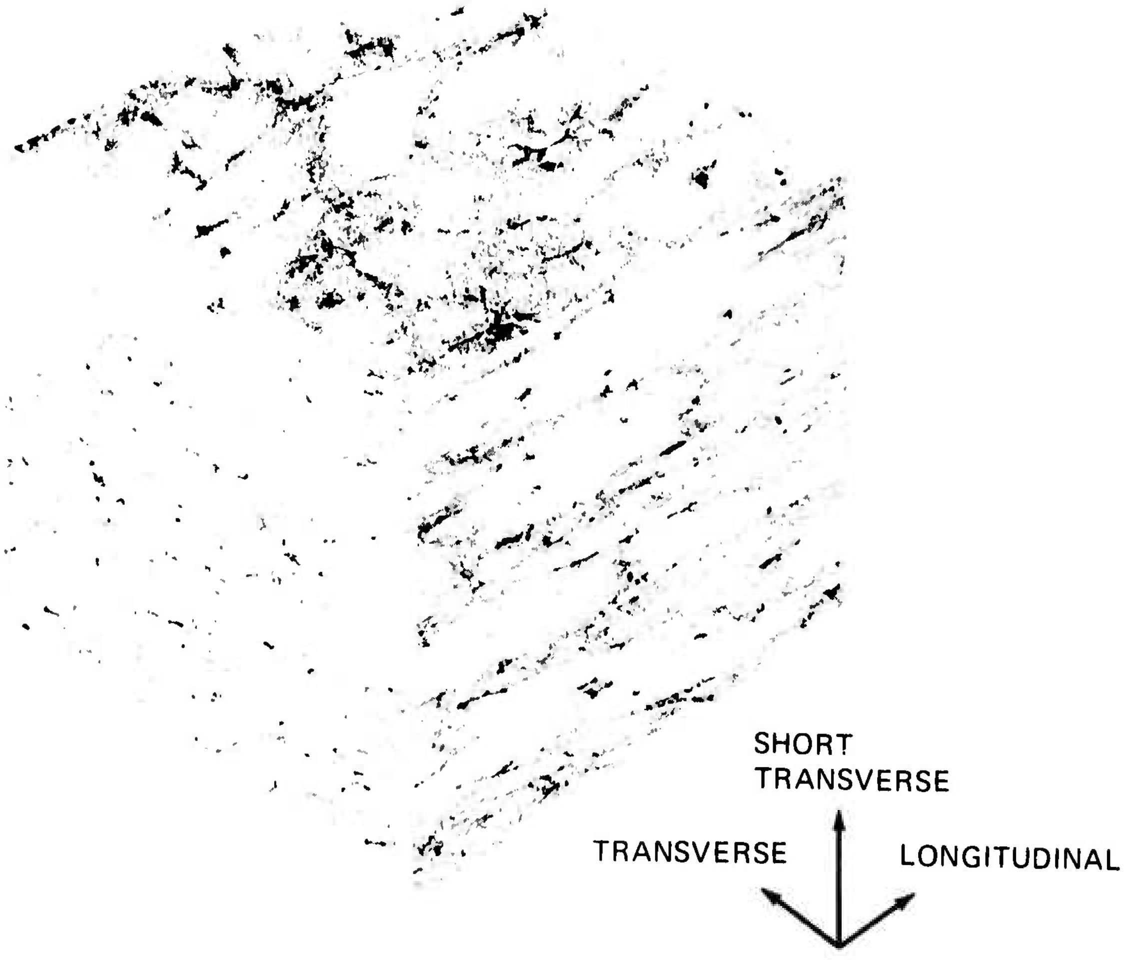


Figure 46. Microstructure at Center of 3-Inch-Thick Plate of Alloy 21 (75X)

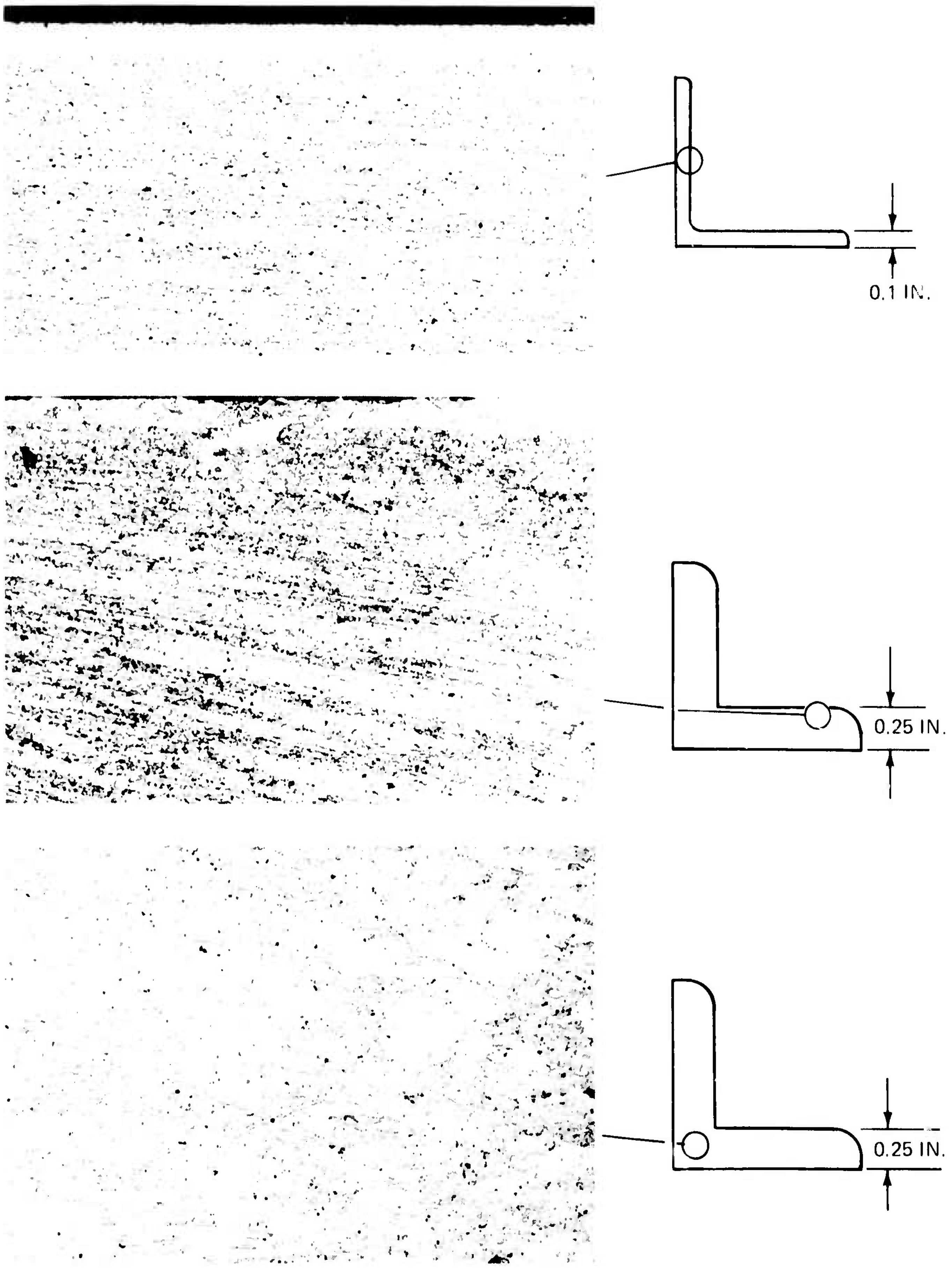


Figure 47. Microstructures of Transverse Specimens from 0.1-Inch-Thick and 0.25-Inch-Thick Extrusions of Alloy 21 (100X)

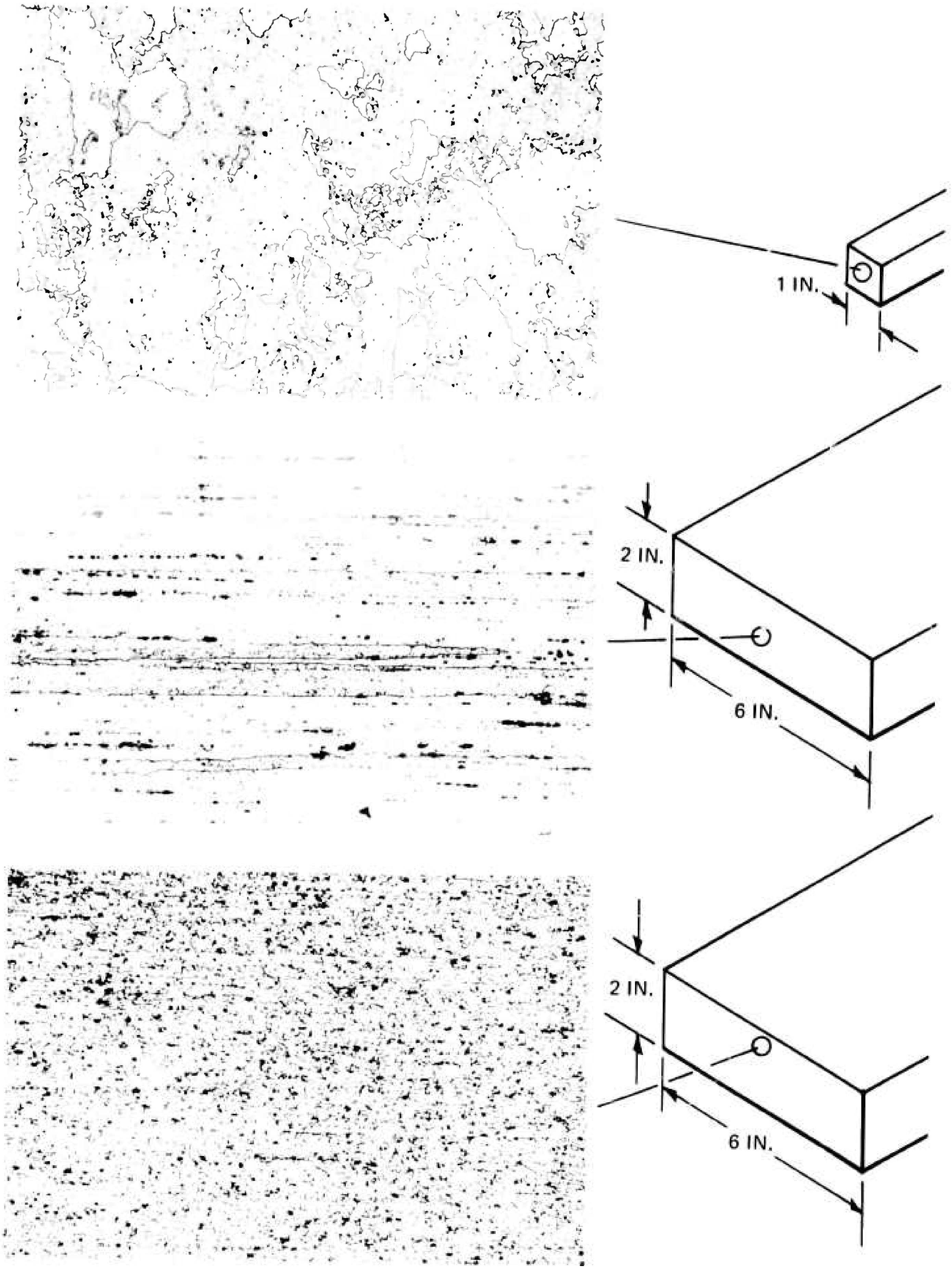


Figure 48. Microstructures of Transverse Specimens from 1-Inch-Thick and 2-Inch-Thick Extrusions of Alloy 21 (100 X)

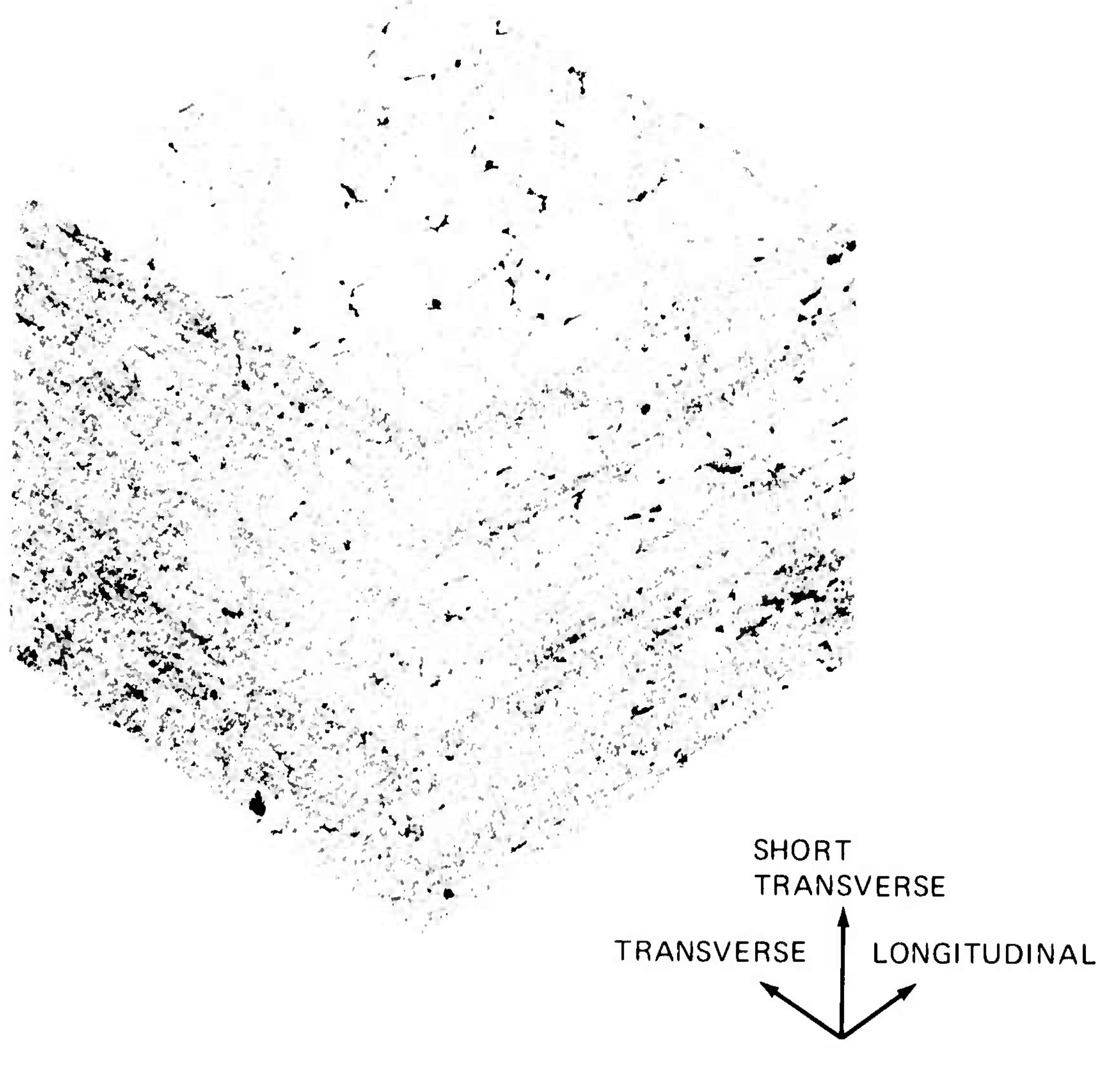


Figure 49. Microstructure at Center of the 6- by 9.5- by 30-Inch Hand Forging of Alloy 21 (75X)

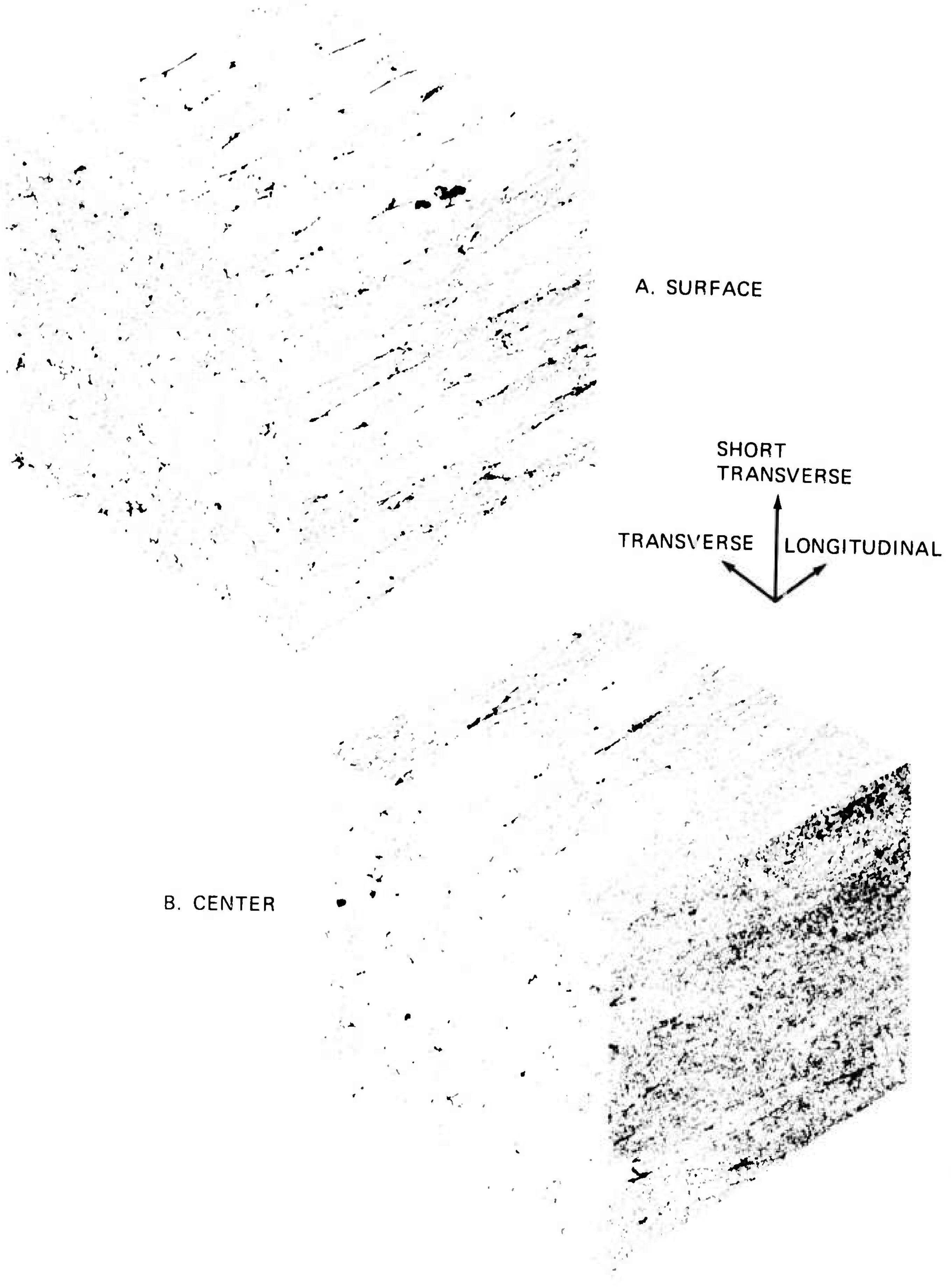
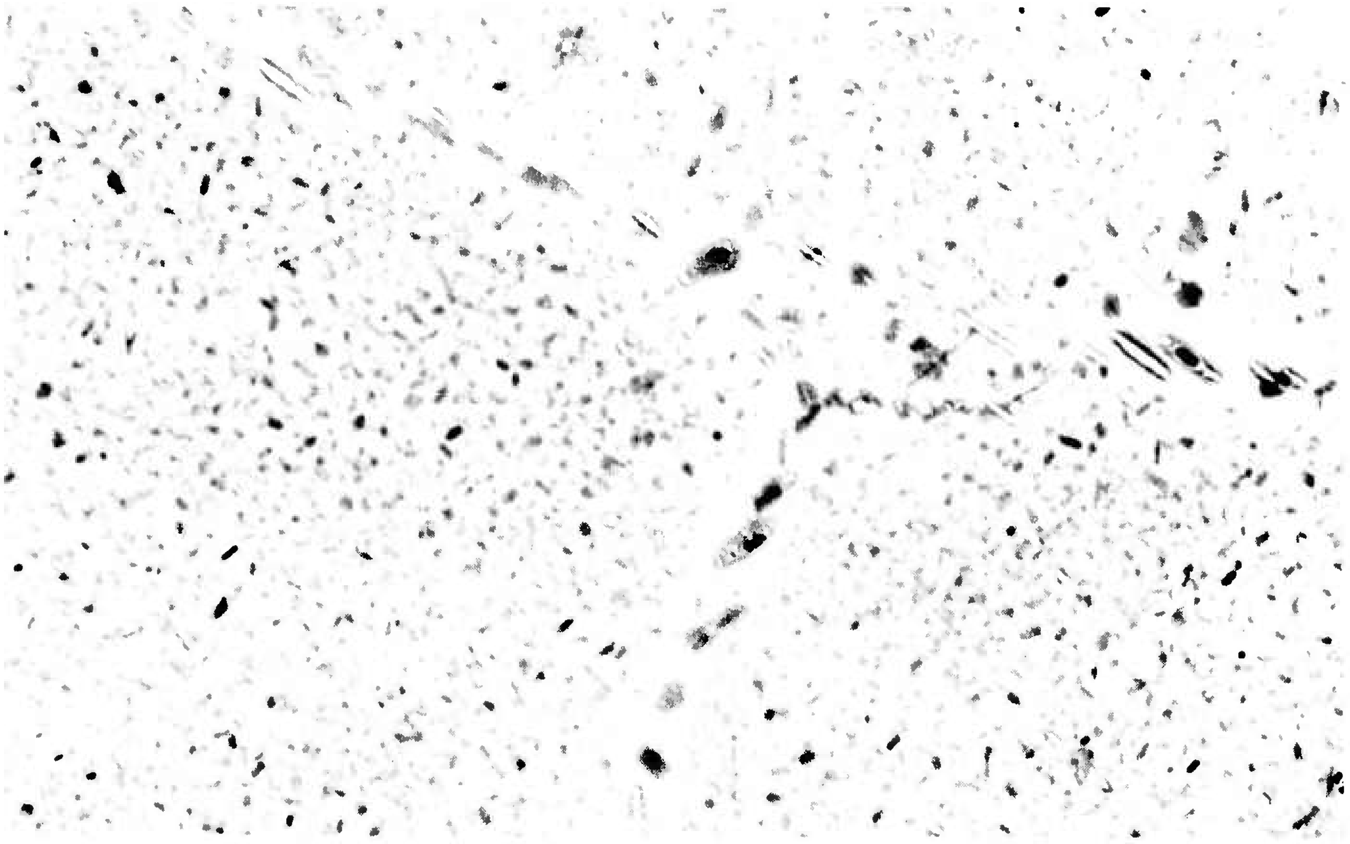
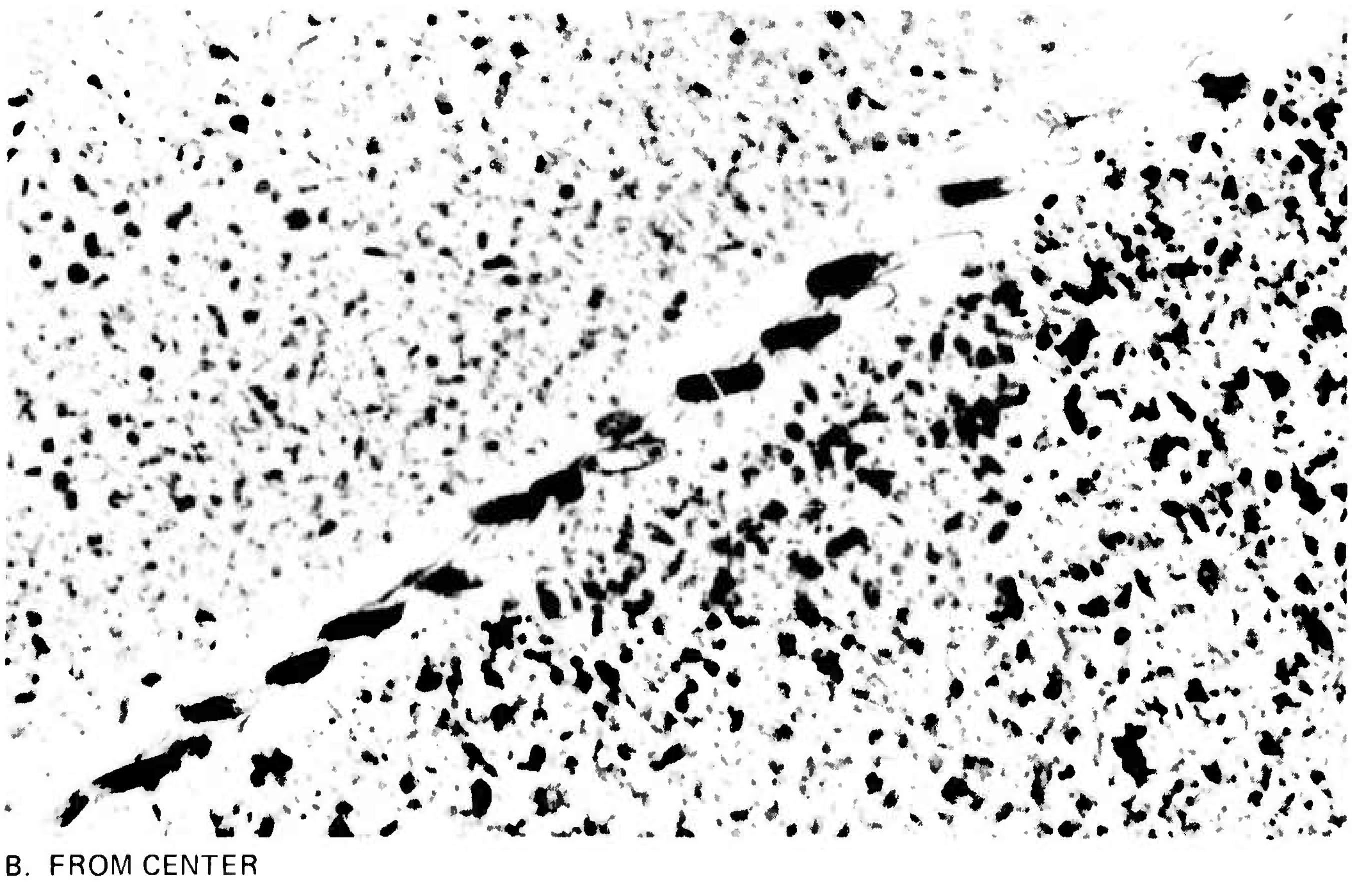


Figure 50. Microstructure at the Surface and Center of the 6.75-Inch-Diameter Landing Gear Die Forging (75X)



A. FROM NEAR SURFACE



B. FROM CENTER

Figure 51. Typical Transmission Electron Micrographs of Specimens from 6.75-In.-Diameter by 33-In.-Long Die Forging of Alloy 21 (Solution Treated at 870°F for 7 Hr, Quenched in 75°F Water, 1 Hr at Room Temperature + 24 Hr at 250°F + 35 Hr at 325°F. Heatup Rate from Room Temperature to 250°F and from 250°F to 325°F Was 35°F/Hr) (113,000X)

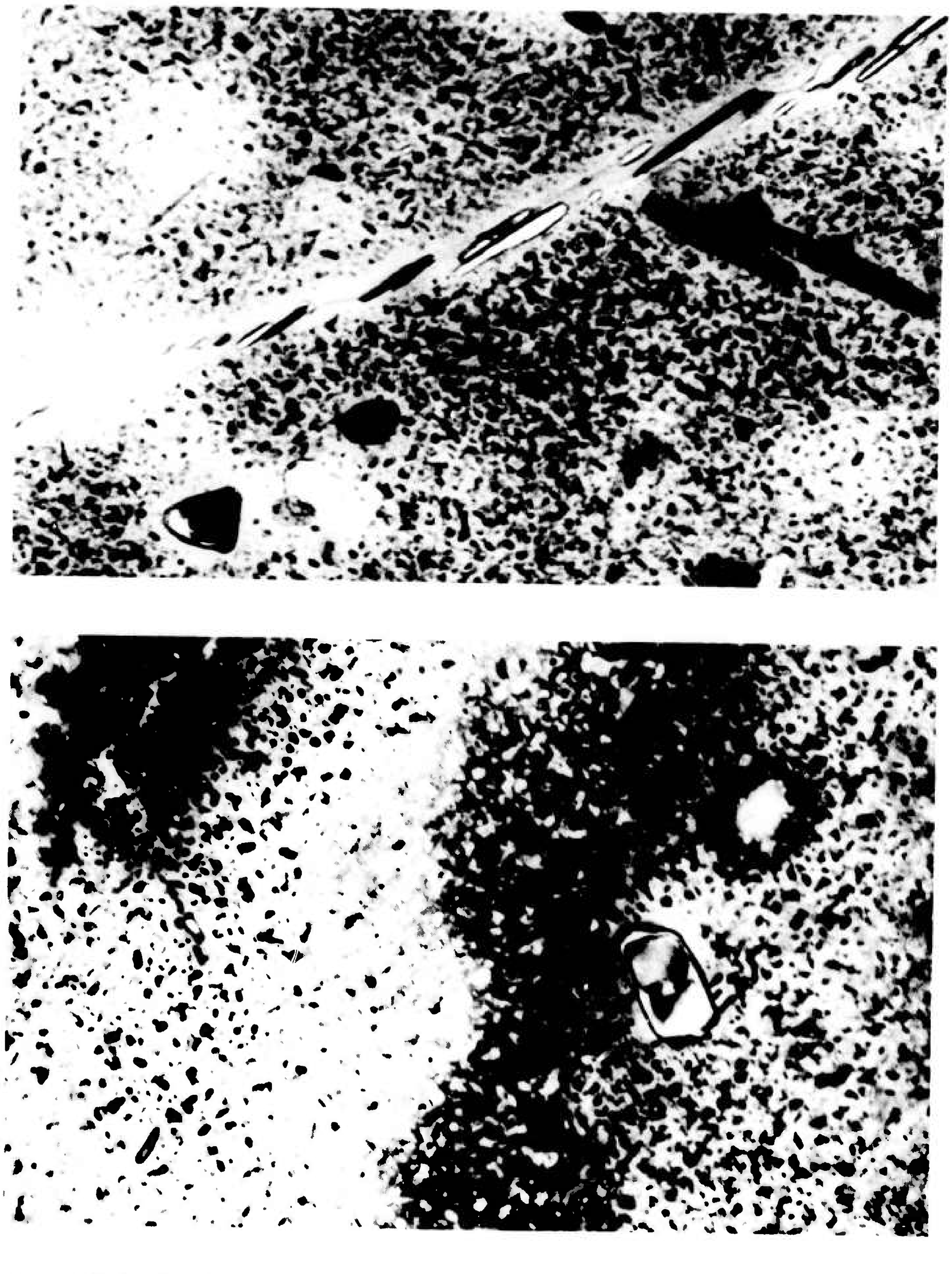


Figure 52. Typical Transmission Electron Micrographs of Specimens from the Center of a 4.5-In.-Diameter Die Forging of Kaiser's 7049-T73 (Heat Treatment Proprietary) (113,000X).

Table 7. Average Tensile Ultimate Strength Results for Alloy 21[a]

Alloy product form	Overall dimension (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Tensile ultimate strength (ksi)				
				Longitudinal		Long transverse	Short transverse	
				Center	Surface	Center	Center	Surface
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	74.1[b]	75.7	–	70.5[b]	74.7
Die forging (Navajo type)	4 x 6 x 55	4	4	74.4[c]	74.5	72.5	70.7	–
		0.75	0.75	77.4	–	77.3	–	–
Hand forging	6 x 10 x 45 } 6 x 9.5 x 30 }	6	6	72.6[b]	–	–	70.5[b]	–
	6 x 10 x 45	6	3	74.8	–	–	72.0	–
		6	1	73.0	–	–	72.3	–
Plate	3 x 20 x 43	3	3	75.5	–	72.3	72.7	–
Extruded angle	0.1 x 0.1 x 140 ft	0.1	0.1	76.3	–	–	–	–
Extruded angle	0.25 x 0.25 x 84 ft	0.25	0.25	77.7	–	–	–	–
Extruded bar	1 x 1 x 40 ft	1	1	80.8	–	–	–	–
Extruded panel	2 x 6 x 38 ft	2	2	77.9	–	–	75.3	–

[a]Each value is an average of tests on two or three tension specimens.

[b]From two forgings.

[c]From three forgings.

Table 8. Average 0.2% Tensile Yield Strength Results for Alloy 21[a]

Alloy product form	Overall dimension (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Tensile ultimate strength (ksi)				
				Longitudinal		Long transverse	Short transverse	
				Center	Surface	Center	Center	Surface
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	66.0[b]	67.8	—	61.8[b]	66.4
Die forging (Navajo type)	4 x 6 x 55	4	4	66.4[c]	66.2	63.2	61.7	—
		0.75	0.75	71.1	—	69.5	—	—
Hand forging	6 x 10 x 45 } 6 x 9.5 x 30 }	6	6	63.4[b]	—	—	62.9[b]	—
	6 x 10 x 45	6	3	66.3	—	—	63.0	—
		6	1	64.6	—	—	62.6	—
Plate	3 x 20 x 43	3	3	66.2	—	63.9	63.4	—
Extruded angle	0.1 x 0.1 x 140 ft	0.1	0.1	67.5	—	—	—	—
Extruded angle	0.25 x 0.25 x 84 ft	0.25	0.25	69.5	—	—	—	—
Extruded bar	1 x 1 x 40 ft	1	1	75.1	—	—	—	—
Extruded panel	2 x 6 x 38 ft	2	2	70.8	—	—	67.5	—

[a]Each value is an average of tests on two or three tension specimens.
[b]From two forgings.
[c]From three forgings.

Table 9. Average Elongation Results for Alloy 21[a]

Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Elongation (% in 1 in.)				
				Longitudinal		Long transverse	Short transverse	
				Center	Surface	Center	Center	Surface
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	13[b]	15	—	8[b]	7
Die forgings (Navajo type)	4 x 6 x 55	4	4	15[c]	15	10	7	—
		0.75	0.75	15	—	14	—	—
Hand forgings	6 x 10 x 45 } 6 x 9.5 x 30 }	6	6	13[b]	—	—	5[b]	—
	6 x 10 x 45	6	3	14	—	—	10	—
		6	1	15	—	—	10	—
Plate	3 x 20 x 43	3	3	11	—	9	6	—
Extruded angle	0.1 x 0.1 x 140 ft	0.1	0.1	4[d]	—	—	—	—
Extruded angle	0.25 x 0.25 x 84 ft	0.25	0.25	6[d]	—	—	—	—
Extruded bar	1 x 1 x 40 ft	1	1	13	—	—	—	—
Extruded panel	2 x 6 x 38 ft	2	2	15	—	—	16[e]	—

[a]Each value is an average of tests on two or three 1/4-in.-diam (1-in. gage length) tension specimens unless otherwise indicated.
[b]From two forgings.
[c]From three forgings.
[d]2-in. gage-length specimens.
[e]0.5-in. gage-length specimens.

Table 10. Average Reduction in Area Results for Alloy 21[a]

Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Reduction in area (%)				
				Longitudinal		Long transverse	Short transverse	
				Center	Surface	Center	Center	Surface
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	35.1[b]	41.6	—	10.8[b]	8.8
Die forging (Navajo type)	4 x 6 x 55	4	4	40.5[c]	41.7	13.2	7.9	—
		0.75	0.75	43.5	—	41.5	—	—
Hand forging	6 x 10 x 45 } 6 x 9.5 x 30 }	6	6	26.9[b]	—	—	5.4[b]	—
	6 x 10 x 45	6	3	33.3	—	—	8.3	—
		6	1	41.8	—	—	15.5	—
Plate	3 x 20 x 43	3	3	21.4	—	11.1	7.4	—
Extruded angle	0.1 x 0.1 x 140 ft	0.1	0.1	21.0	—	—	—	—
Extruded angle	0.25 x 0.25 x 84 ft	0.25	0.25	27.8	—	—	—	—
Extruded bar	1 x 1 x 40 ft	1	1	40.3	—	—	—	—
Extruded panel	2 x 6 x 38 ft	2	2	41.3	—	—	12.3	—

[a]Each value is an average of tests on two or three tension specimens.
[b]From two forgings.
[c]From three forgings.

Table 11. Average 0.2% Compressive Yield Strength Results for Alloy 21[a]

Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	0.2% Compressive yield strength (ksi)			
				Longitudinal		Short transverse	
				Center	Surface	Center	Surface
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	71.0	72.4	67.8	71.4
Die forging (Navajo type)	4 x 6 x 55	4	4	69.5[b]	–	66.4[b]	–
Hand forging	6 x 10 x 45	6	6	69.4	–	67.9	–
		6	3	69.1	–	68.4	–
		6	1	69.1	–	69.3	–
Plate	3 x 20 x 43	3	3	71.0	–	–	–
Extruded bar	1 x 1 x 40 ft	1	1	77.8	–	–	–
Extruded panel	2 x 6 x 38 ft	2	2	75.6	–	–	–

[a]Each value is an average of tests on two or three compression specimens.

[b]From two forgings.

Table 12. Average Ultimate Shear Strength Results for Alloy 21[a]

Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Ultimate shear strength (ksi)			
				Longitudinal		Short transverse	
				Center	Surface	Center	Surface
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	–	52.0	–	49.0
Die forging (Navajo type)	4 x 6 x 55	4	4	47.4[b]	–	46.4[b]	–
Hand forging	6 x 10 x 45	6	6	47.9	–	44.9	–
		6	3	48.6	–	46.9	–
		6	1	49.2	–	48.7	–
Plate	3 x 20 x 43	3	3	48.5	–	47.2	–

[a]Each value is an average of tests on two shear specimens.

[b]From two forgings.

Table 13. Average Bearing Ultimate Strength Results for Alloy 21[a]

Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Bearing ultimate strength (ksi)							
				Center				Surface			
				E/D[b] = 1.5		E/D[b] = 2.0		E/D[b] = 1.5		E/D[b] = 2.0	
				L	ST	L	ST	L	ST	L	ST
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	106.0	–	137.8	–	115.1	115.7[c]	151.6	152.6[c]
Hand forging	6 x 10 x 45	6	6	108.6	112.0	141.0	147.1	–	–	–	–
		6	3	113.0	112.8	148.5	146.9	–	–	–	–
		6	1	113.1	109.4	148.9	140.0	–	–	–	–

[a]Each value is an average of tests on two bearing specimens.

[b]E/D denotes edge margin to hole diameter ratio.

[c]Examination of specimens revealed that the grain flow in the test section was longitudinal rather than short transverse.

Table 14. Average 0.2% Bearing Yield Strength Results for Alloy 21[a]

Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	0.2% Bearing yield strength (ksi)							
				Center				Surface			
				$E/D^b = 1.5$		$E/D^b = 2.0$		$E/D^b = 1.5$		$E/D^b = 2.0$	
				L	ST	L	ST	L	ST	L	ST
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	88.4	–	105.8	–	93.0	105.8[c]	110.8	132.3[c]
Hand forging	6 x 10 x 45	6	6	90.4	93.4	107.8	112.6	–	–	–	–
		6	3	94.3	92.6	107.1	109.1	–	–	–	–
		6	1	91.1	89.2	109.1	105.3	–	–	–	–

[a]Each value is an average of tests on two bearing specimens.

[b]E/D denotes edge margin to hole diameter ratio.

[c]Examination of specimens revealed that the grain flow in the test section was longitudinal rather than short transverse.

Specification minimums for 7075-T6 and 7075-T73. That 2-in. rather than 1-in. gage length tension specimens of angular extrusions were used may account for the lower elongation values for these products. Reduction in area values were satisfactory for tests in all grain directions. Shear properties (Table 12) were consistent. Bearing ultimate and bearing yield strengths (Tables 13 and 14) were very similar for die and hand forgings. Surface property values were somewhat higher than center property values.

Expected minimum mechanical properties for hand and die forgings of alloy 21 may be compared with established minimums for several 7000 series alloys in Figs. 53 through 55. The yield strength minimums of alloy 21 were derived by subtracting 6 ksi from the average values, since this is the difference between typical and minimum values for other 7000 series alloys. This procedure appears warranted since the compositions of the wrought products were in the center of the specified composition range for alloy 21 and the microstructures were typical of properly processed forgings. Although these calculated minimums are useful for comparison purposes, they do not represent statistically reliable minimum values for design purposes. Insufficient lots of material were evaluated to establish such statistically reliable minimums.

In die forgings (Fig. 53), alloy 21 has higher minimum tensile yield and ultimate strengths than X7080-T7 and 7075-T73 and just slightly lower minimums than 7049-T73 in section thicknesses below about 4 to 5 in. In section thicknesses above 5 in., however, alloy 21 may have equal or higher strengths than 7049-T73.

In hand forgings (Fig. 54), alloy 21 has higher minimum tensile ultimate strengths than X7080-T7 and 7075-T73 and just slightly lower minimums than 7049-T73 in section thicknesses less than about 4 in. In section thicknesses greater than 4 in., alloy 21 and 7049-T73 are comparable. On a minimum yield strength basis, alloy 21 appears to be superior to 7049-T73 in thicknesses above about 4 in. In thicknesses above 5 in., alloy 21 is even superior to 7075-T6 and comparable to 7079-T6.

Minimum compression values (Fig. 55) indicate that alloy 21 has properties intermediate between 7075-T73 and 7075-T6 or 7079-T6.

5. FRACTURE TOUGHNESS PROPERTIES OF WROUGHT PRODUCTS OF ALLOY 21

Averaged fracture toughness results for alloy 21 were obtained using 1.0-in.-thick three-point bending specimens and the procedures outlined in Ref. 36. Average results are shown in Table 15. Actual data are given in Tables 42 and 43, Appendix III. The values in Table 15 indicate that the plane strain fracture toughness values for alloy 21 are equivalent to those for 7075-T6 and 7075-T73 (37).

Figures 56 through 58 show the fracture surfaces of all toughness specimens tested. The long-transverse and short-transverse specimens were very flat, with no shear lip formation. All but two longitudinal specimens contained large shear lips; except for these two specimens (340L and 341L, Fig. 56), tests on the longitudinal specimens were invalid. A fractography study of short-transverse fracture toughness specimens showed fracture modes ranging from intergranular to ductile transgranular (Fig. 59).

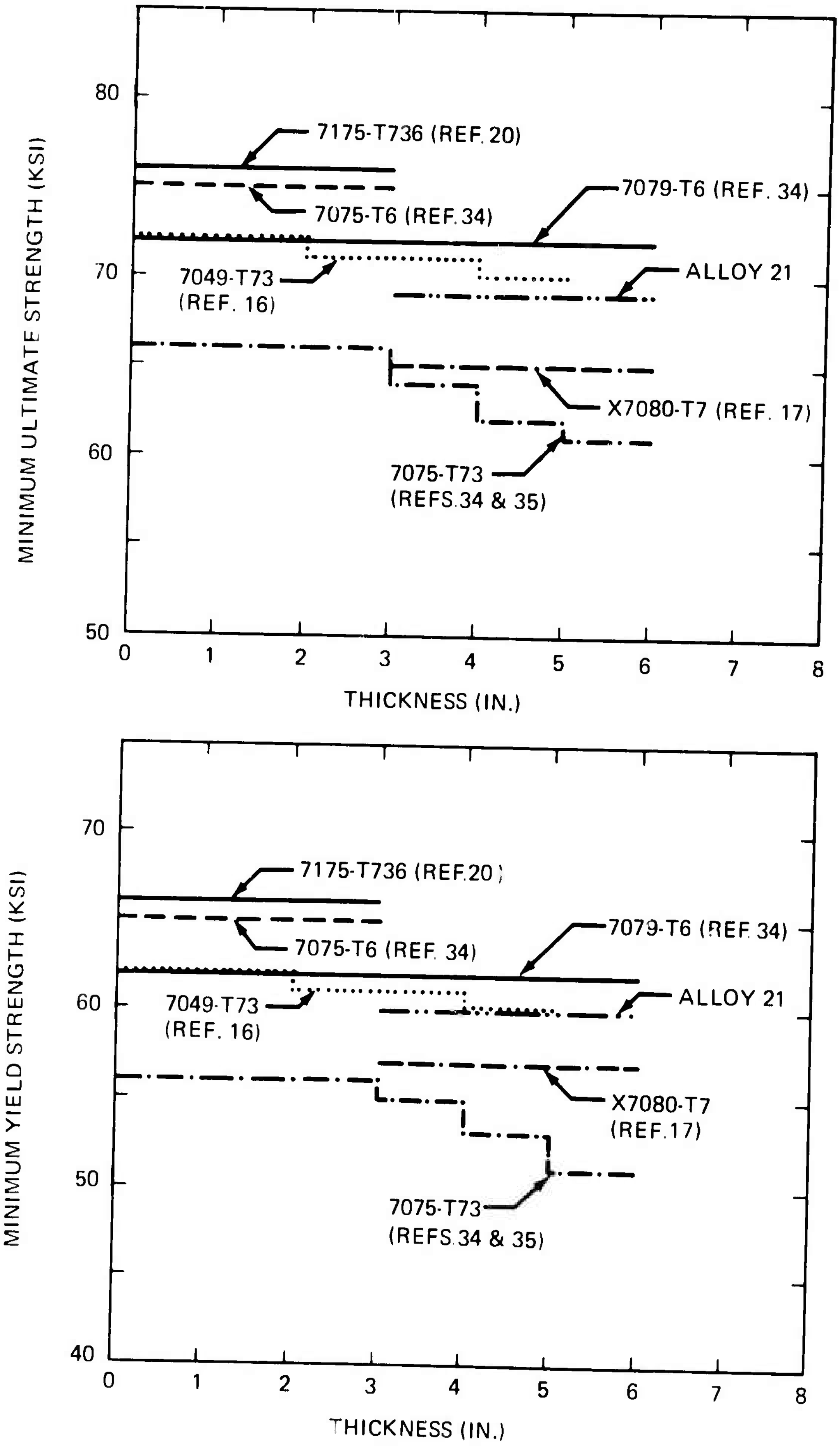


Figure 53. Minimum Longitudinal Ultimate and Yield Strength Values for Die Forgings of Several Commercial Alloys and Alloy 21

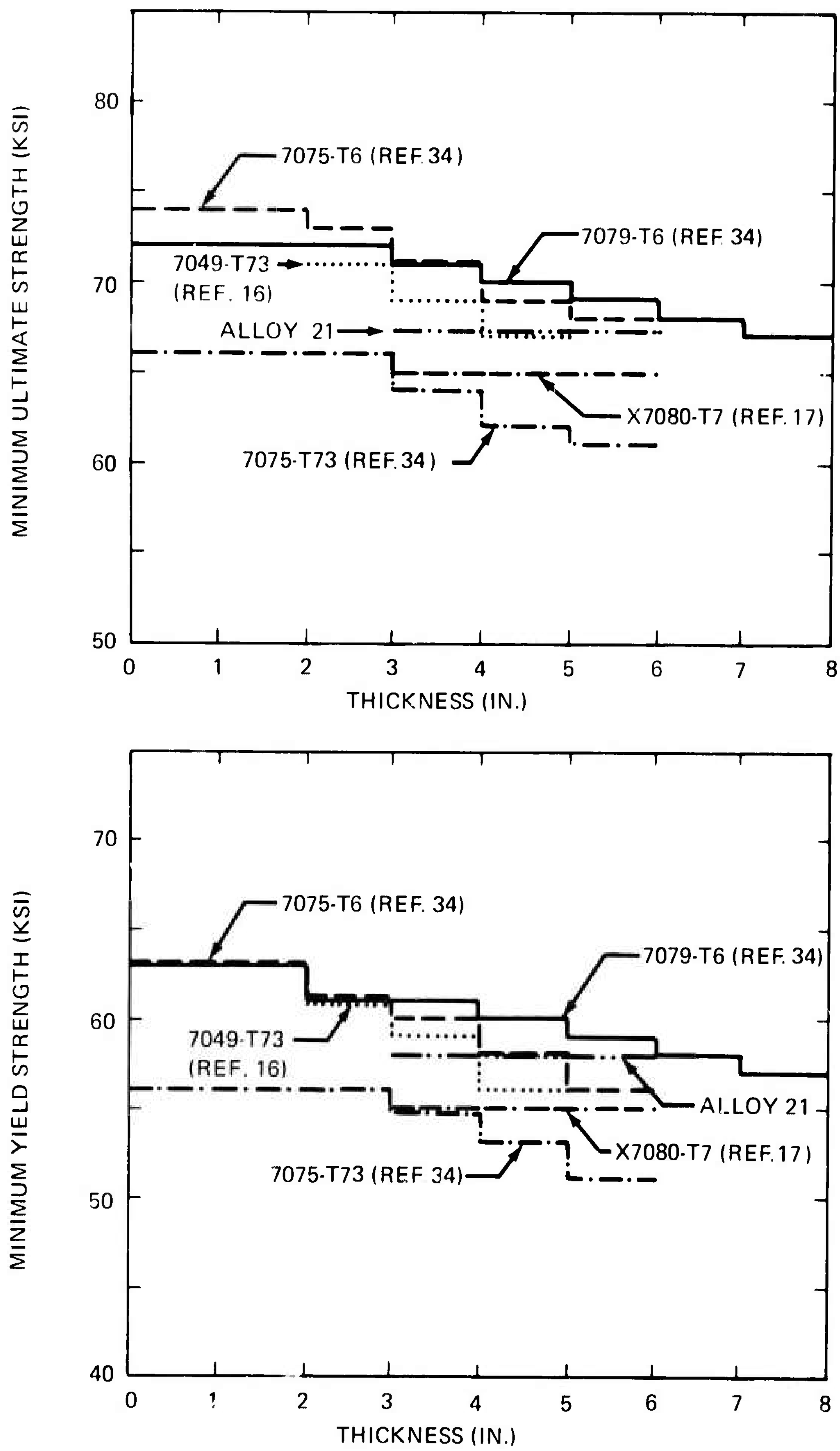


Figure 54. Minimum Longitudinal Ultimate and Yield Strength Values for Hand Forgings of Several Commercial Alloys and Alloy 21

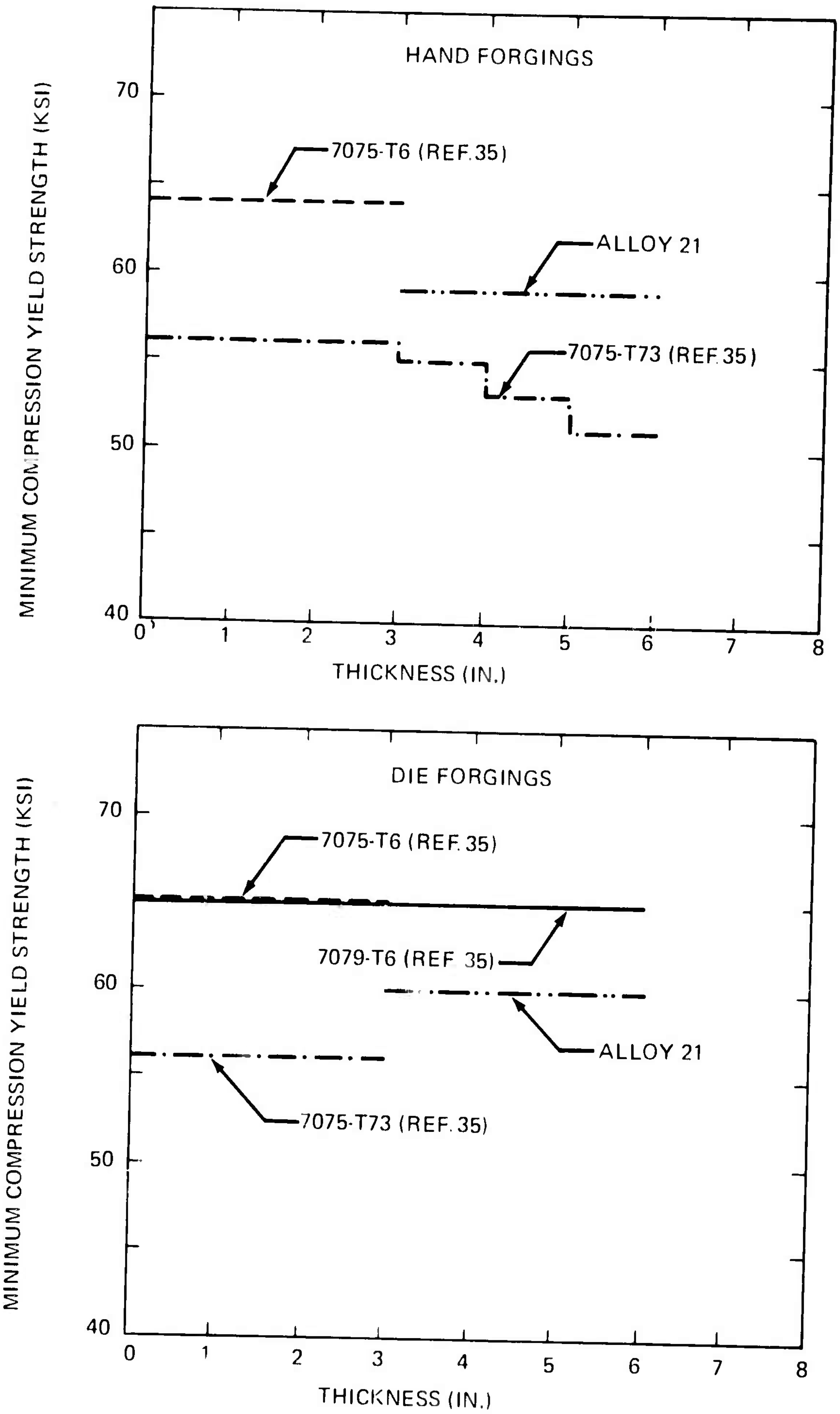


Figure 55. Minimum Longitudinal Compression Yield Strength Values for Hand and Die Forgings of Several Commercial Alloys and Alloy 21

Table 15. Average Plane-Strain Fracture Toughness Results for Alloy 21[a]

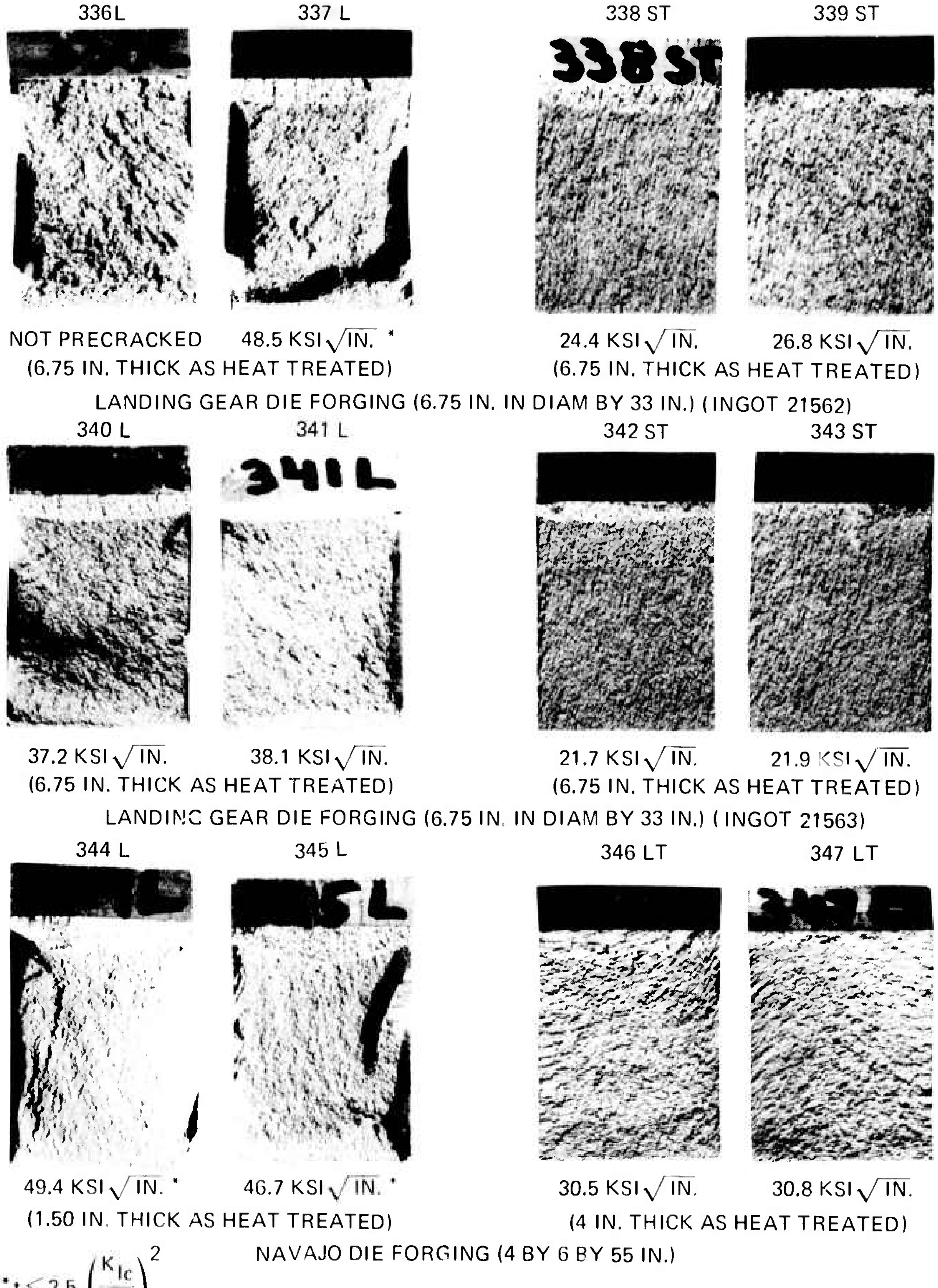
Alloy product form	Overall dimensions (in.)	As-fabricated thickness (in.)	As-heat-treated thickness (in.)	Plane-strain fracture toughness, K_{Ic} (ksi$\sqrt{\text{in.}}$)		
				Longitudinal (center)	Long transverse (center)	Short transverse (center)
Die forging (landing gear)	6.75 diam x 33	6.75	6.75	48.5[c]	–	25.6
	6.75 diam x 33[b]	6.75	6.75	37.7	–	21.8
Die forging (Navajo type)	4 x 6 x 55	4	4	–	30.7[d]	–
		1.5	1.5	48.1[c]	–	–
Hand forging	6 x 10 x 45	6	6	43.9[c]	–	27.3
		6	3	47.5[c]	–	–
		6	1	50.9[c]	–	–
Plate	3 x 20 x 43	3	3	48.2[c]	32.3	28.9
Extruded panel	2 x 6 x 38 ft	2	2	59.6[c]	–	–

[a]Each value is an average of tests on two 1-in.-thick specimens in three point bending.

[b]This forging contained some inclusions.

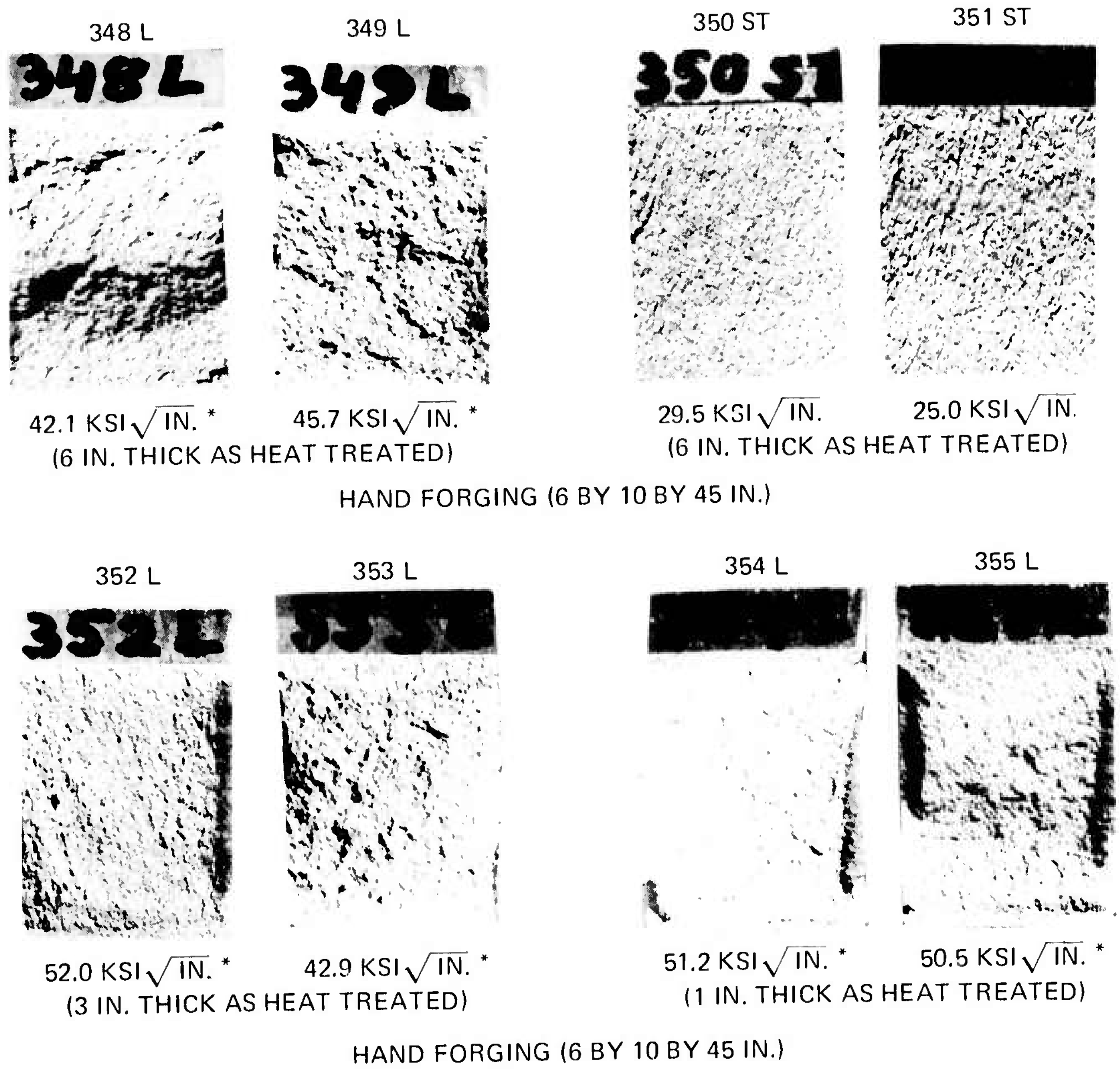
[c]
$$t < 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$$

[d]From two forgings.



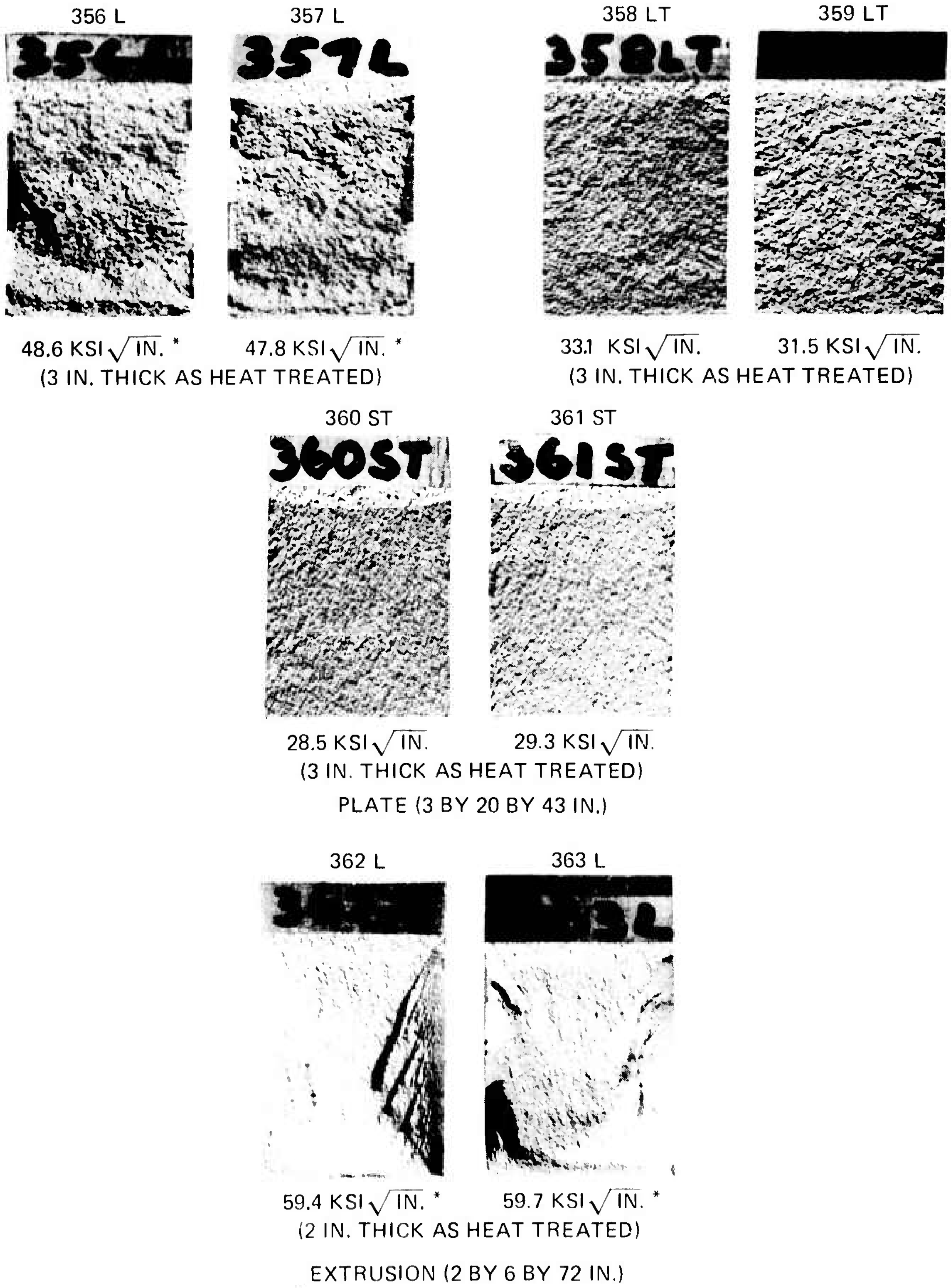
$^{*}t < 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$

Figure 56. Fracture Surfaces of Notched Bend Fracture Toughness Specimens from Alloy 21 Die Forgings (L = Longitudinal, LT = Long Transverse, ST = Short Transverse) (1.1X)



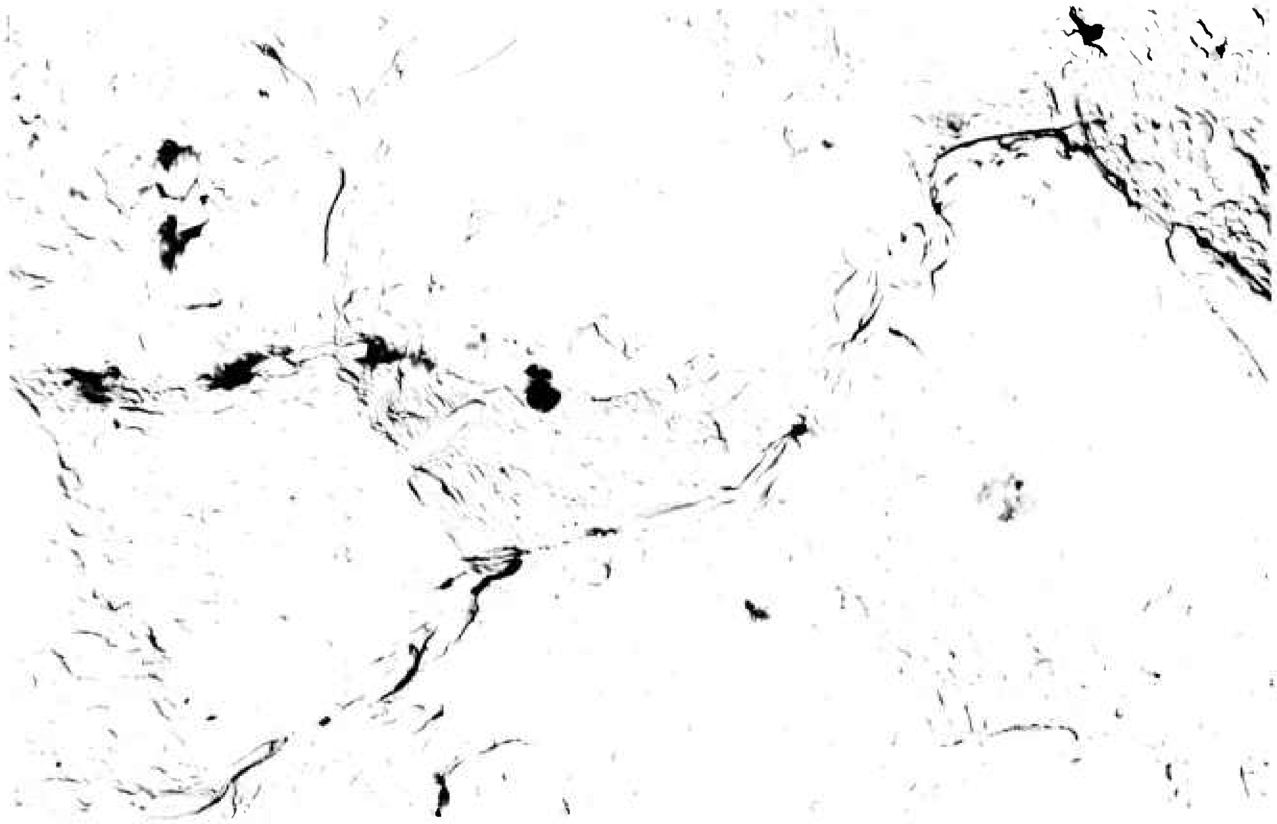
* $t < 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}} \right)^2$

Figure 57. Fracture Surfaces of Notched Bend Fracture Toughness Specimens from Alloy 21 Hand Forgings (L = Longitudinal, ST = Short Transverse) (1.1X)

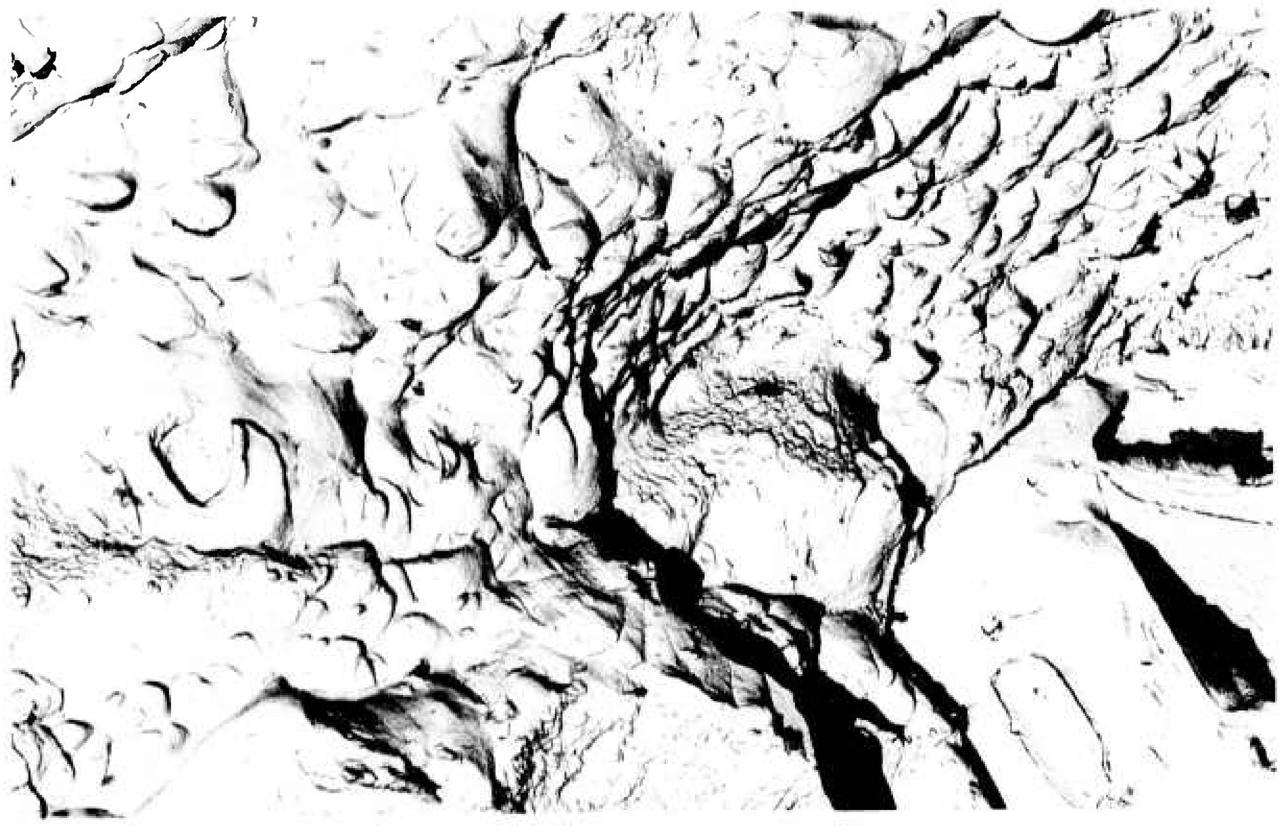


$* \; t < 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}} \right)^2$

Figure 58. Fracture Surfaces of Notched Bend Fracture Toughness Specimens from Alloy 21 Plate and Extrusions (L = Longitudinal, LT = Long Transverse, ST = Short Transverse) (1.1X)



A. SPECIMEN 339ST



B. SPECIMEN 343ST

Figure 59. Typical Electron Fractographs of Short-Transverse Fracture Toughness Specimens of Landing Gear Die Forgings of Alloy 21. Fractures Ranged from Intergranular (A) to Ductile Transgranular (B) (6,100 X).

6. FATIGUE PROPERTIES OF WROUGHT PRODUCTS OF ALLOY 21

The test results on notched and unnotched fatigue specimens of alloy 21 (R = 0.1) may be compared with scatterbands for 7075-T6 (R = 0.0) in Figs. 60 through 63. Fatigue test data are tabulated in Tables 44 through 47, Appendix III. In the notched condition the fatigue strength of alloy 21 is similar to that of 7075-T6. The notched fatigue properties are essentially the same for all product forms of alloy 21. Except in the short-transverse grain direction, the data on unnotched specimens of alloy 21 (Fig. 60) are within or near the established scatterband for longitudinal and long-transverse 7075-T6 products. For tests on unnotched short-transverse specimens, data for alloy 21 are again comparable to data for 7075-T6 and 7075-T73 die forgings in the short-transverse grain direction (Fig. 60).

7. STRESS-CORROSION RESULTS ON WROUGHT PRODUCTS OF ALLOY 21

a. Double Cantilever Beam Tests

Double cantilever beam (DCB) specimens of the type shown in Fig. 26 were machined from the heat-treated hand and die forgings, extrusions, and plate of alloy 21. For the hand forgings, extrusions, and plate, the specimens were machined from the center of the parts to test the transverse or short-transverse structure. For the die forgings, the specimens were machined from near the surface across the parting plane to test the most short-transverse structure possible. The longitudinal axes of the DCB specimens were parallel to the longitudinal grain directions for all products.

Test results for these specimens are shown in Fig. 64. For comparison, the maximum growth rates obtained from Ref. 26 for X7080-T7, 7178-T76, 7175-T736, AZ74.61, 7049-T73, and 7075-T73 are indicated along the ordinate. Except for one specimen from the Navajo die forging, all growth rates were less than that of X7080-T7. It should be noted that the X7080-T7 data in Fig. 64 is from a DCB specimen machined from the center of an 8-in.-thick die forging where the grain structure was nearly equiaxed, whereas the specimen from the Navajo die forging of alloy 21 was from across the parting plane in an area where a very short-transverse structure existed.

b. Smooth-Specimen Tests in 3.5% NaCl (Alternate Immersion) and Industrial Atmosphere

Smooth-specimen stress-corrosion tests were performed using three different specimen types. Configurations for these specimens are shown in Figs. 71, 79, and 80, Appendix III. The stressing frame and tension stress-corrosion specimen employed for industrial atmosphere testing, together with the loading jig, are shown in Fig. 65. The industrial atmosphere test facility for these specimens, Fig. 66, is located on top of a two-story engineering building at Boeing-Renton and faces south.

Figure 67 shows a stressed and masked tuning-fork-type stress-corrosion specimen. This specimen and the 0.25-in.-diam deadweight loaded tension stress-corrosion specimen were used for the 3.5% NaCl alternate-immersion tests. The tuning-fork specimen is particularly useful for testing die forgings in the short-transverse direction right at the parting plane or for testing thin plate (0.25 in. thick or greater) in the short-transverse direction.

SPECIMEN TYPE	ALLOY	R	K_t	GRAIN DIR L	GRAIN DIR ST	INGOT NO. (REF.)
SMOOTH	ALLOY 21	0.1	1.0	○	△	21562
	7075-T6	0.0	1.0		⊘	(REF. 38)
	7075-T73	0.0	1.0		⊘	(REF. 38)
NOTCHED	ALLOY 21	0.1	3.0	●	▲	21562
					■	21563[a]

[a]CONTAINS SMALL INCLUSIONS

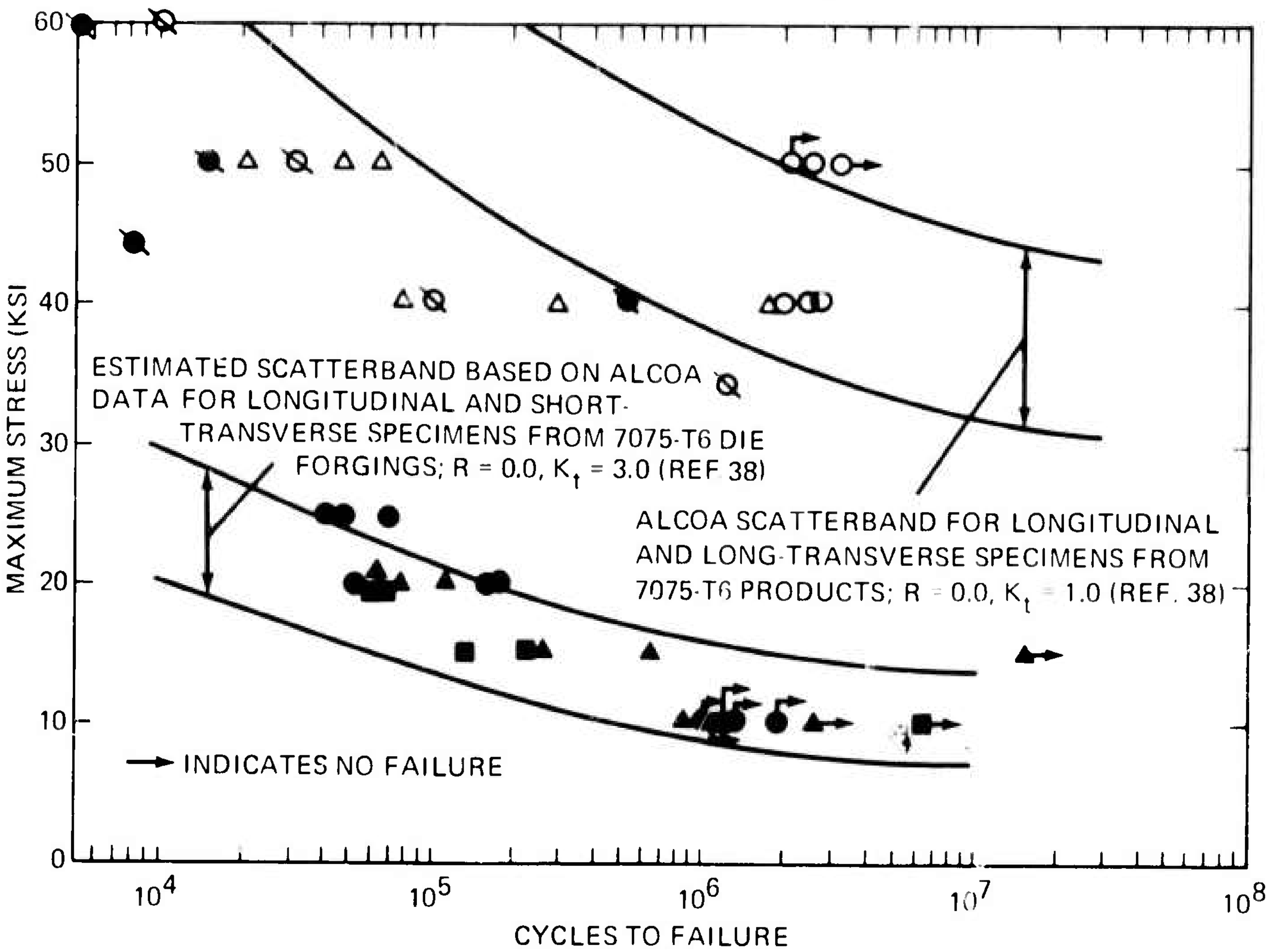


Figure 60. Tension-Tension Fatigue Results for Specimens Machined from the Center of 6.75-Inch-Diameter Landing Gear Die Forging of Alloy 21

SPECIMEN TYPE	R	K_t	GRAIN DIR L	GRAIN DIR ST	INGOT NO.
NOTCHED	0.1	3.0	●	▲	21562

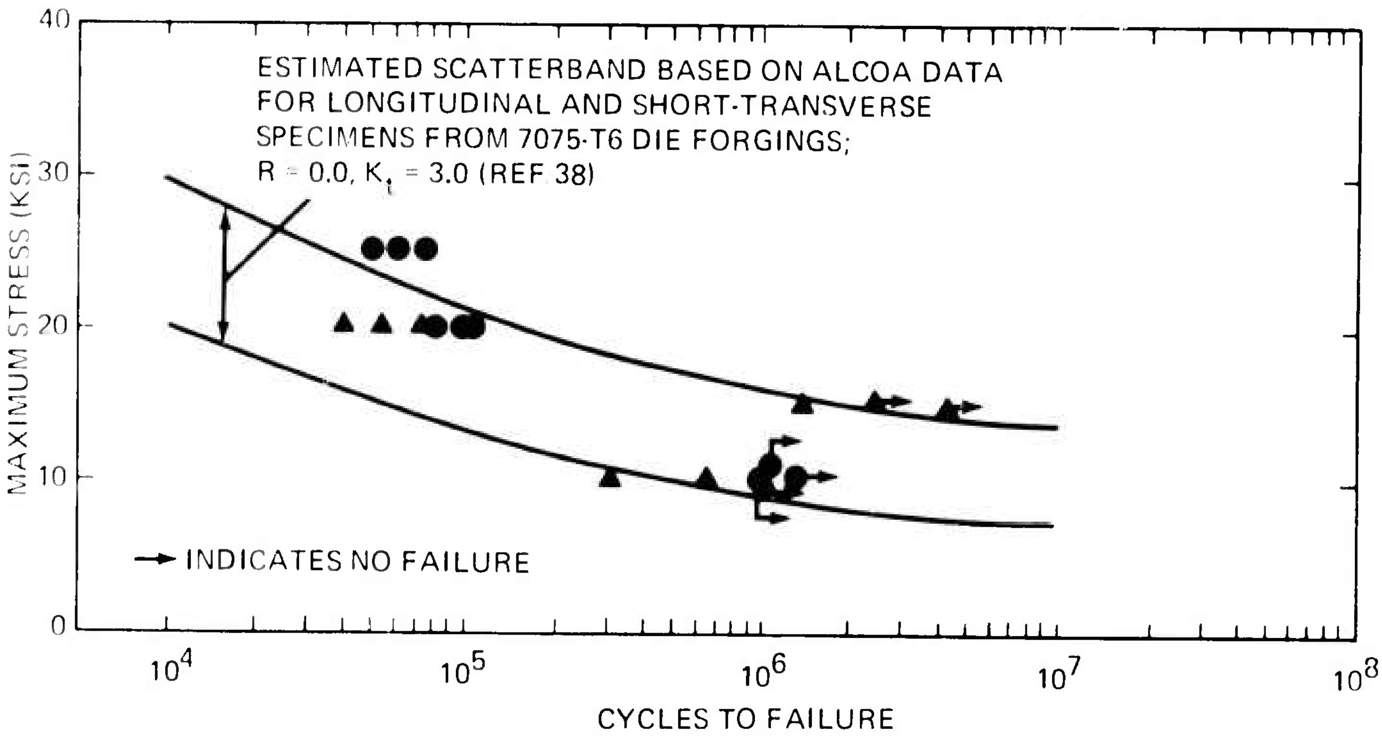


Figure 61. Tension-Tension Fatigue Results for Specimens Machined from the Center of 6- by 10- by 45-In. Hand Forging of Alloy 21. As-Heat-Treated Thickness Was 6 In.

SPECIMEN TYPE	R	K_t	GRAIN DIR L	GRAIN DIR ST	INGOT NO.
NOTCHED	0.1	3.0	●	▲	21562

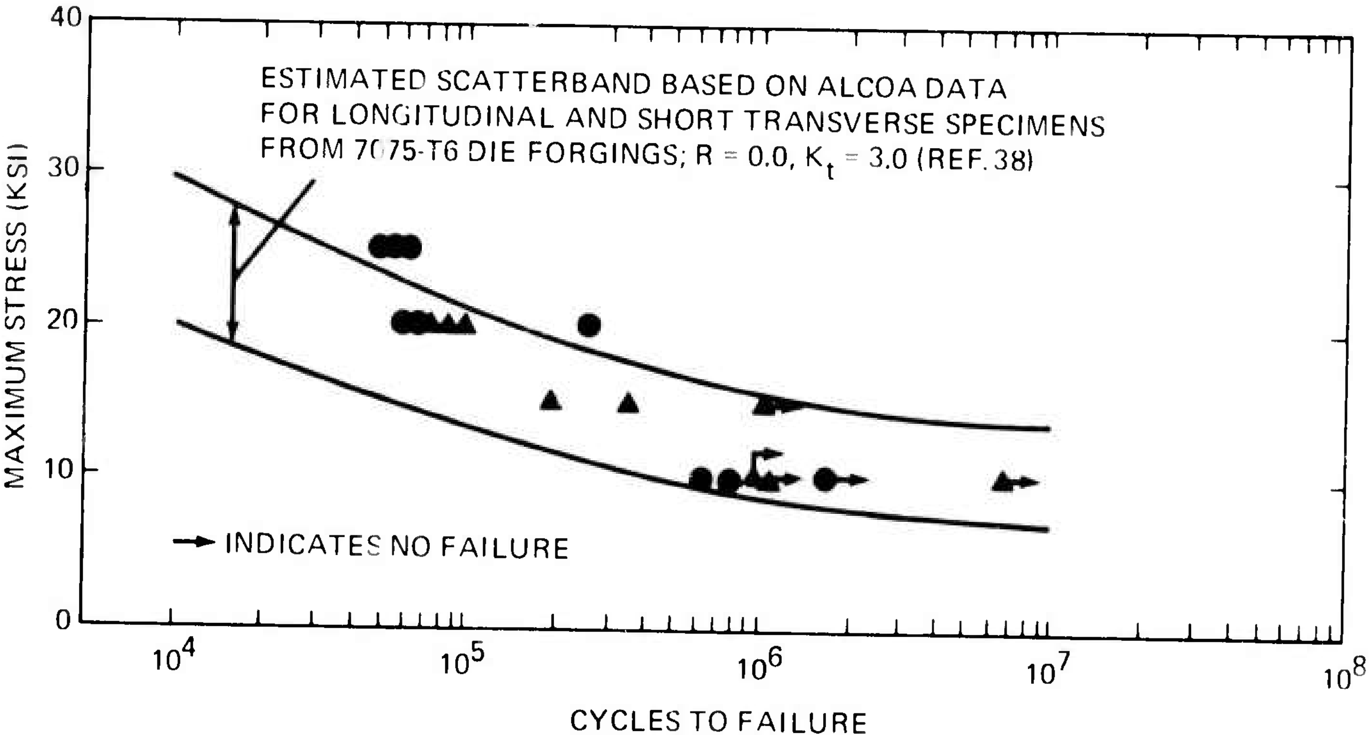


Figure 62. Tension-Tension Fatigue Results for Specimens Machined from the Center of 6- By 10- By 45-In. Hand Forging of Alloy 21. As-Heat-Treated Thickness Was 1 In.

SPECIMEN TYPE	R	K_t	GRAIN DIR. L.	INGOT NO.
NOTCHED	0.1	3.0	●	21565

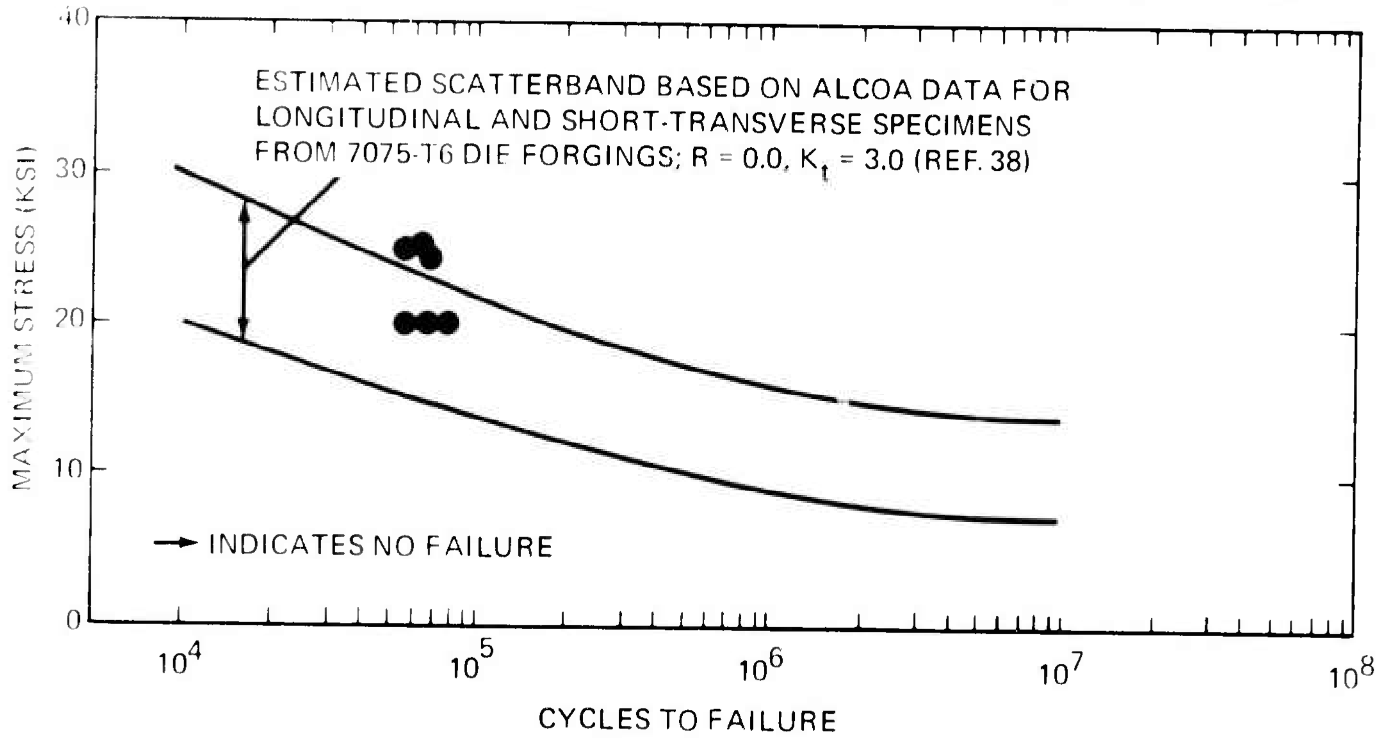


Figure 63. Tension-Tension Fatigue Results for Specimens Machined from the Center of 2- by 6- by 72-In. Extrusion of Alloy 21

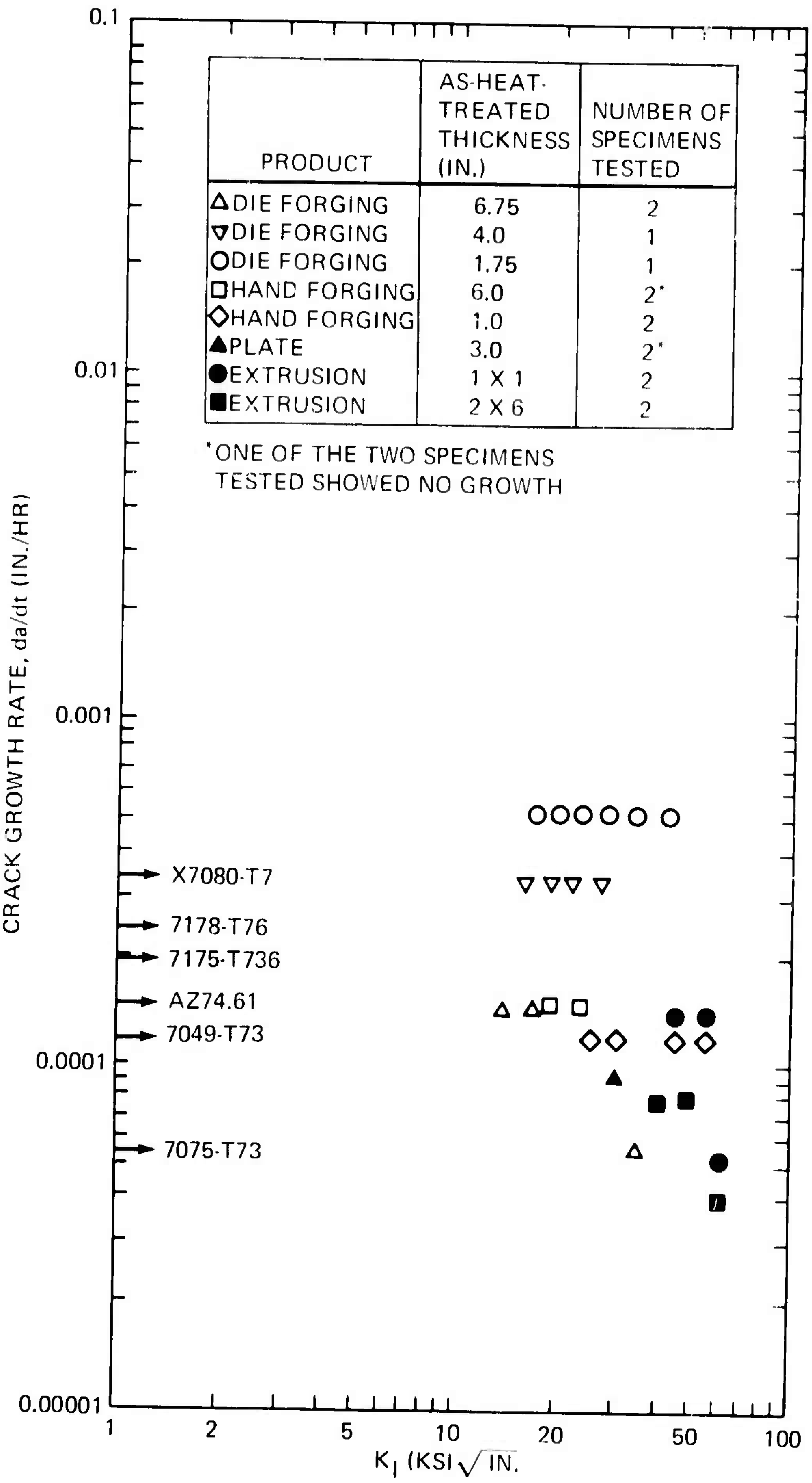
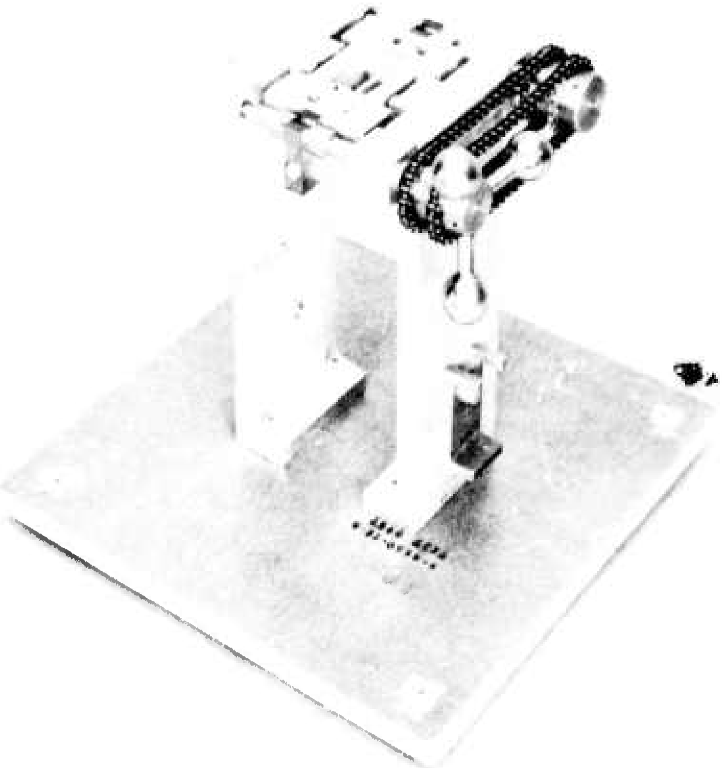
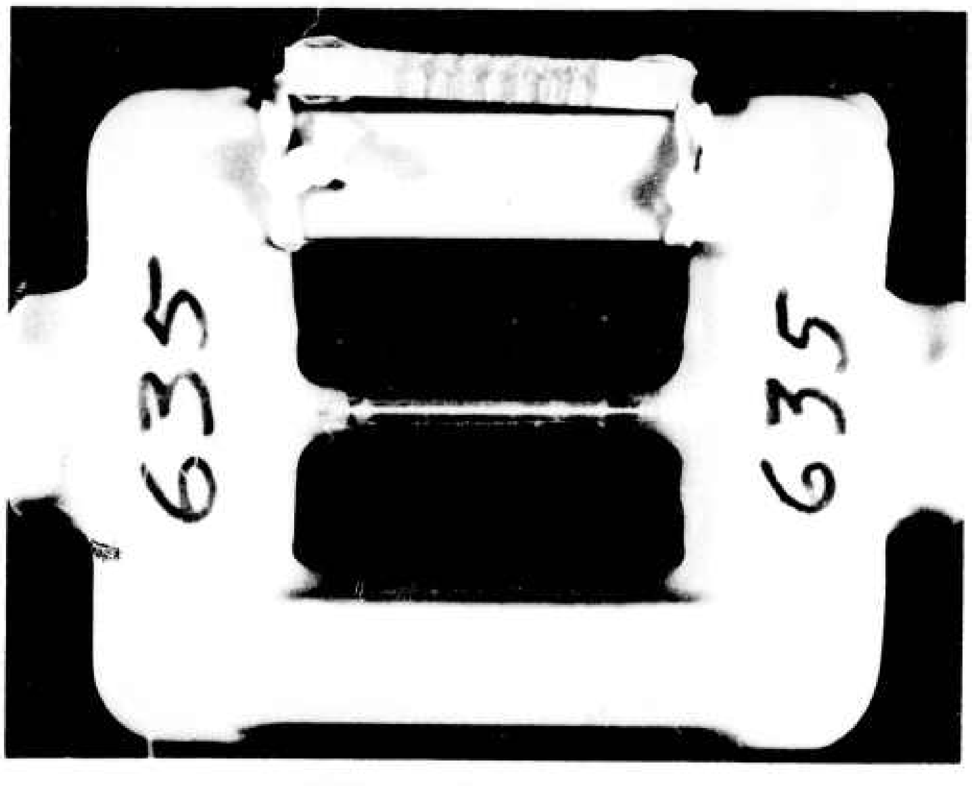


Figure 64. Stress-Corrosion Cracking Behavior of Alloy 21 Wrought Products Measured on Precracked DCB Specimens Intermittently Wetted with 3.5% NaCl. All Specimens Were Machined to Test the Material in the Transverse or Short-Transverse Direction. Maximum Crack Growth Rates for the Commercial Alloys Are from Ref. 26.

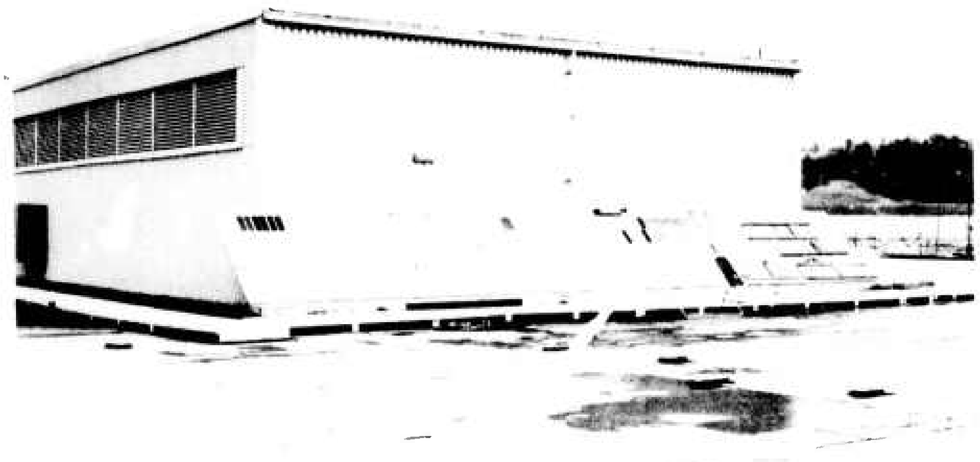


A. DURING LOADING IN LOADING JIG

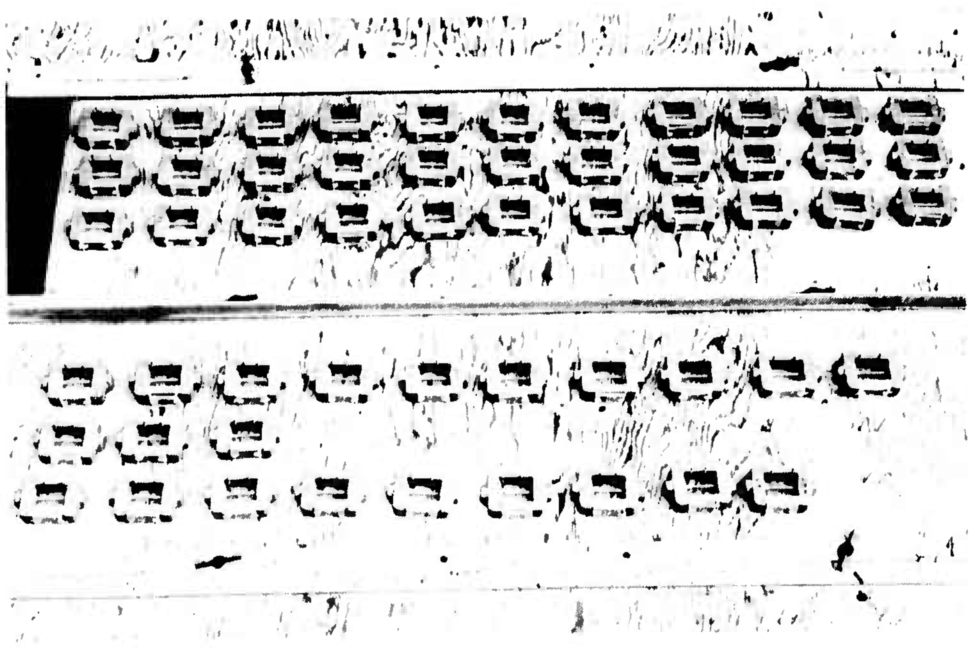


B. AFTER LOADING AND MASKING

Figure 65. Stressing Frame and Tension Stress-Corrosion Specimen



A.



B.

Figure 66. Industrial Atmosphere Test Facility (A) and Rack of Test Specimens (B)

Figure 67. Stressed and Masked Battelle-Type Stress-Corrosion Specimen

Short-transverse stress-corrosion results to date are given in Tables 16 through 19. None of the deadweight loaded specimens tested by alternate immersion at or below 35 ksi failed (Tables 16 and 17). Evaluation of results from tuning-fork specimens must await metallographic examination of sectioned specimens. After 136 days no failures have occurred in tension stress-corrosion specimens exposed to the industrial environment. The industrial environment tests will continue until 1973.

Table 16. Stress-Corrosion Test Results on Short-Transverse Specimens from Die Forgings of Alloy 21 (3.5% NaCl Alternate Immersion)

Alloy product form	Specimen location	Specimen type	Heat treatment[a] Quench medium	Heat treatment[a] Aging treatment	Heat treatment[a] As-heat treated-thickness (in.)	Specimen no.	Stress level (ksi)	Days to failure
6.75-in.-diam landing gear (ingot 21562)	Surface	Battelle	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6.75	322	50	d
						323		
						325		
						319	35	
						321		
						326		
						318	25	
						324		
						320		
		Dead load				249	50	34
						248	35	88[c]
						247	25	88[c]
	Center[b]					253	50	34
						252	35	88[c]
						250	25	88[c]
						251		88[c]
						254		88[c]
4 x 6- x 55-in. Navajo (ingot 21562)	Surface	Battelle			2.4	329	50	d
						332		
						335		
						328	35	
						331		
						334		
						327	25	
						330		
						333		

[a]Heatup rates from room temperature to 250°F and from 250°F to 325°F were 35°F/hr. Room-temperature delay time between quench and start of aging was 1 hr.

[b]Cooling rate in center of forging was ≈ 14°F/sec.

[c]Specimen did not fail after days shown and was removed from test.

[d]Determination whether or not stress-corrosion failure occurred must await metallurgical examination of sectioned specimens.

Table 17. Stress-Corrosion Test Results on Short-Transverse Specimens from Hand Forging, Plate, and Extrusion of Alloy 21 (3.5% NaCl Alternate Immersion)

Alloy product form	Specimen location	Specimen type	Heat treatment[a]: Quench medium	Heat treatment[a]: Aging treatment	Heat treatment[a]: As-heat-treated thickness (in.)	Specimen no.	Stress level (ksi)	Days to failure
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	257	50	34
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	260	50	34
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	263	50	34
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	256	35	88[c]
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	259	35	88[c]
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	262	35	88[c]
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	255	25	88[c]
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	258	25	88[c]
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6	261	25	90[c]
3.0- x 20- x 43-in. plate	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	3	266	50	34
3.0- x 20- x 43-in. plate	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	3	265	35	88[c]
3.0- x 20- x 43-in. plate	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	3	268	35	85
3.0- x 20- x 43-in. plate	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	3	264	25	96[c]
3.0- x 20- x 43-in. plate	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	3	267	25	96[c]
2- x 6- x 72-in. extruded panel	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	2	271	50	53
2- x 6- x 72-in. extruded panel	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	2	270	35	88[c]
2- x 6- x 72-in. extruded panel	Center[b]	Dead load	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	2	269	25	88[c]

[a]Heatup rates from room temperature to 250°F and from 250°F to 325°F were 35°F/hr. Room-temperature delay time between quench and start of aging was 1 hr.

[b]Cooling rate in center of hand forging, plate, and extruded panel was approximately 10°F/sec, 20°F/sec, and 70°F/sec, respectively.

[c]Specimen did not fail after days shown and were removed from test.

Table 18. Stress-Corrosion Test Results on Short-Transverse Specimens from Die Forgings of Alloy 21 (Industrial Atmosphere, Renton, Washington)

Alloy product form	Specimen location	Specimen type	Heat treatment[a]: Quench medium	Heat treatment[a]: Aging treat-ment	Heat treatment[a]: As-heat-treated thickness (in.)	Specimen no.	Stress level (ksi)	Days to failure
6.75-in.-diam landing hear (ingot 21562)	Surface	Stress frame type	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	6.75	278	50	136[e]
						273 275	35	
						274 277	25	
						272 276	15	
	Center[c]					283 281	35	
						282 280	25	
						279	15	
(ingot 21563)[b]						292 291	50	
						288 286 290	35	
						287 285 289	25	
						284	15	

Table 18.—Concluded

Alloy product form	Specimen location	Specimen type	Heat treatment[a]: Quench medium	Heat treatment[a]: Aging treat-ment	Heat treatment[a]: As-heat-treated thickness (in.)	Specimen no.	Stress level (ksi)	Days to failure
4- x 6- x 55-in. Navajo (ingot 21562)	Surface	Stress frame type	75°F water	T6 (24hr at 250°F) +35hr at 325°F	2.4	293	35	136[e]
						295	35	136[e]
						297	25	136[e]
						294	25	136[e]
						296	15	136[e]

[a]Heatup rates from room temperature to 250°F and from 250°F to 325°F were 35°F/hr. Room-temperature delay time between quench and start of aging was 1 hr.

[b]This ingot contained inclusions.

[c]Cooling rate in center of forging was ≈ 14°F/sec.

[d]Specimens 283, 281, 282, 280, and 279 were taken from indentical respective locations in one forging as were specimens 288, 286, 287, 285, and 284 in the other.

[e]Denotes that specimen did not fail after days shown and is still in test. Scheduled test period is 3 yr.

Table 19. Stress-Corrosion Test Results on Short-Transverse Specimens from Hand Forging, Plate, and Extrusion of Alloy 21 (Industrial Atmosphere, Renton, Washington)

Alloy product form	Specimen type	Specimen location	Heat treatment[a] Quench medium	Aging treat-	As-heat-treated thickness (in.)	Specimen no.	Stress level (ksi)	Days to failure
6- x 10- x 45-in. hand forging (ingot 21562)	Center[b]	Stress frame type	75°F water	T6 (24 hr at 250°F) + 35 hr at 325°F	1	301	50	136[c]
						299	35	
						303	35	
						300	25	
						304	25	
						298	15	
						302	15	
						305	25	
						306	25	
3- x 20- x 43-in. plate					3	308	35	
						311	35	
						307	25	
						309	25	
						310	15	
2- x 6- x 72-in. extruded panel					2	317	50	
						313	35	
						316	35	
						312	25	
						315	25	
						314	15	

[a] Heatup rates from room temperature to 250°F and from 250°F to 325°F were 35°F/hr. Room-temperature delay time between quench and start of aging was 1 hr.

[b] Cooling rate in center was approximately 10°F/sec, 20°F/sec, and 70°F/sec for hand forging, plate, and extrusion respectively.

[c] Denotes that specimen did not fail after days shown and is still in test. Scheduled test period is 3 yr.

SECTION V

DISCUSSION

1. MEETING THE FATIGUE AND FRACTURE TOUGHNESS GOALS

Phase III test results indicate that alloy 21 in the T6 + 35 hr at 325°F temper has fatigue and fracture-toughness properties that are comparable to and possibly better than those of both 7075-T6 and 7075-T73.

2. MEETING THE STRESS-CORROSION GOAL

Although long-term industrial atmosphere stress-corrosion results are not yet complete, crack growth rate data taken from DCB specimens (Figs. 33 and 64) and conclusions from microstructural examination of stress-corrosion specimens from Phase II (Figs. 42 through 45) indicate that the T6 + 35 hr at 325°F aging treatment for alloy 21 will provide a smooth-specimen, stress-corrosion threshold in 3.5% NaCl alternate immersion tests of at least 25 ksi and probably even as high as 35 ksi. This makes it highly probable that alloy 21 heat treated as described can also meet the 25-ksi threshold level in an industrial environment.

3. MECHANICAL PROPERTIES OF ALLOY 21 AND OTHER COMMERCIAL AND EXPERIMENTAL 7000 SERIES ALLOYS

Alloy 21 in the T6 + 35 hr at 325°F temper cannot possibly meet the minimum contract yield strength goal of 70 ksi or even the more recent 63-ksi goal of the Alcoa and Reynolds contracts (8,9). Based on the mechanical-property data shown in Figs. 53 and 54 and on stress-corrosion results, it does appear, however, that alloy 21 can outperform X7080-T7 on a strength basis and at the same time provide the short-transverse stress-corrosion threshold stress of 25 ksi originally intended for X7080-T7 in an industrial environment. The strength of alloy 21 also appears comparable to that of 7049-T73.

To compare alloy 21 with the experimental thick-section alloys that are being developed by Alcoa and Reynolds (8,9,10,11,12,13,14,15), typical yield strength values for the various alloys are shown as a function of quench rate in Fig. 68. Typical yield strength values for X7080-T7, 7049-T73, 7175-T736, 7075-T6, and other alloys were plotted at quench rates determined for each alloy according to part geometry and quench water temperature from Ref. 39, p. 137.

Before the data in Fig. 68 are examined, it should be noted that only some of the more promising of the Alcoa and Reynolds developmental alloys are included. The latest Alcoa alloys (alloys 10 through 18 in Table 1 and Fig. 1), which were cast to replace some vanadium-bearing alloys (alloys 1, 2, 3, 4, and 7 in Table 1), are not included. These vanadium-bearing, chromium-free alloys were replaced because of low elongations that resulted from the formation of extremely coarse, primary intermetallic particles of $Al_{12}Mg_2V$ (14).

ALLOY	SYMBOL	Zn	Mg	Cu	Cr	Mn	Zr	Fe	Si	Ti	Ni
BOEING ALLOY 21	●	6.24	2.50	1.10	< 0.02	0.10	0.13	0.13	0.06	0.02	
REYNOLDS 2	○	6.58	2.39	1.22	< 0.01	< 0.01	0.11	0.07	0.05	0.03	
REYNOLDS 3	¤	6.72	2.46	1.18	< 0.01	< 0.01	0.18	0.06	0.03	0.05	
REYNOLDS 8	△	6.76	2.61	1.22	< 0.01	0.39	< 0.01	0.08	0.04	0.02	
REYNOLDS 13	□	6.78	2.63	1.23	< 0.01	0.30	0.11	0.08	0.05	0.04	
7375 + Mn	■	5.72	2.21	1.52	0.03	0.34	0.01	0.20	0.07	0.04	
7375 + Zr	■	5.80	2.20	1.25	0.01	0.01	0.12	0.25	0.09	0.03	
7080	+	5.88	2.29	0.90	0.01	0.32	0.00	0.13	0.08	< 0.02	
7075	▲	5.82	2.18	1.54	0.20	0.01	0.00	0.30	0.09	0.03	
7175	●	5.37	2.44	1.60	0.21	0.03	0.00	0.12	0.05	0.03	
7049	◆	7.55	2.41	1.33	0.12	< 0.01	0.00	0.11	0.08	0.03	
ALCOA A	▼	5.90	2.20	2.40	0.01	0.34	0.00	—	—	—	
ALCOA 5	-□-	5.82	2.32	2.21	0.05	0.00	0.13	0.09	0.04	0.03	
ALCOA 9	-■-	5.96	2.30	2.37	0.00	0.03	0.12	0.08	0.04	0.03	
BOEING ALLOY 21	◇ -○-	6.24	2.50	1.10	< 0.02	0.10	0.13	0.13	0.06	0.02	

UNLESS OTHERWISE INDICATED BY A TEMPER DESIGNATION OR SPECIFIC HEAT TREATMENT, DATA ARE FROM MATERIAL AGED 24 HR AT 250° F + 18 HR AT 325° F.

GRAIN DIRECTIONS FOR MECHANICAL PROPERTIES ARE AS SHOWN; PROPERTIES ARE FOR PLATE UNLESS OTHERWISE INDICATED.

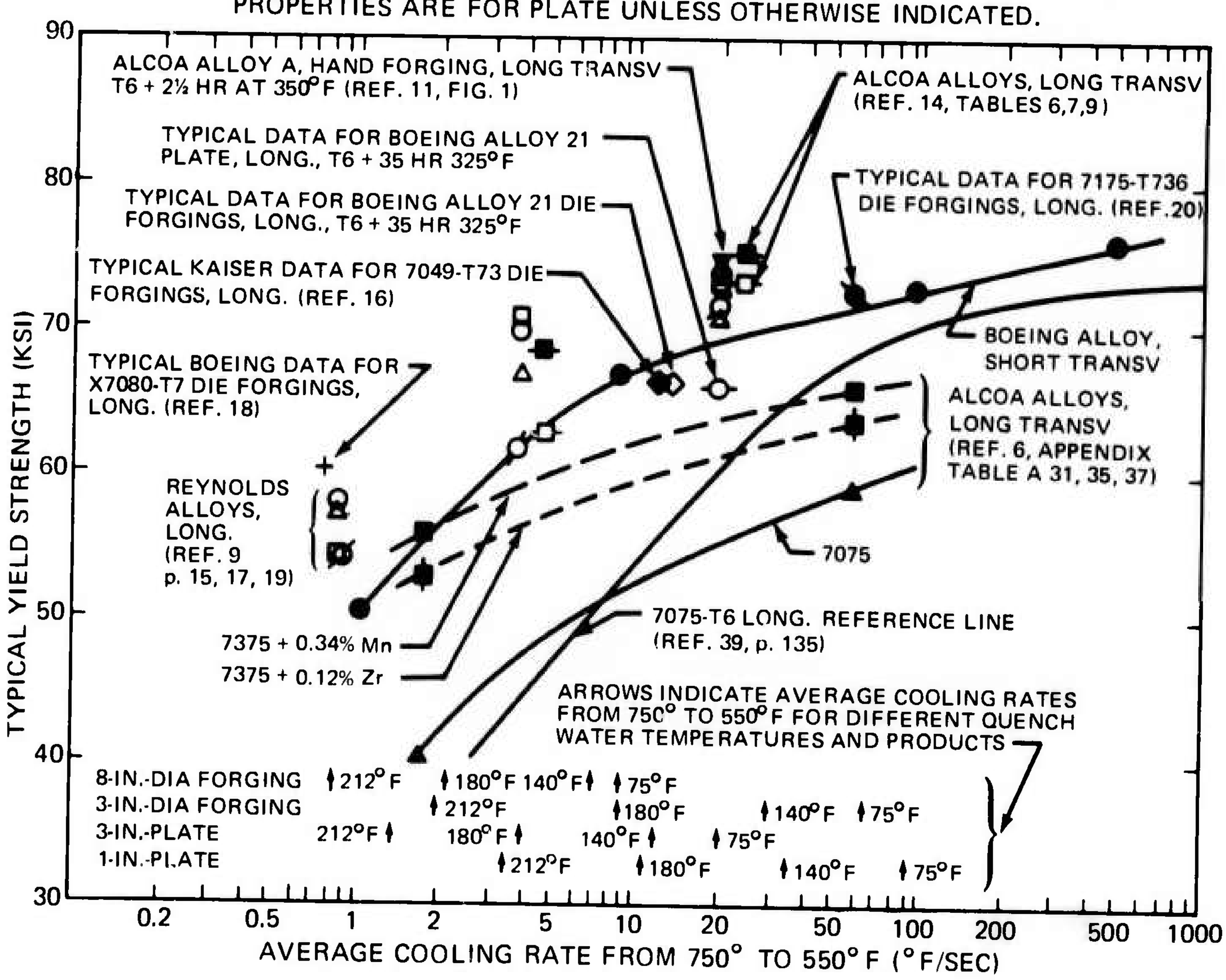


Figure 68. Effect of Quench Rate on Yield Strength of Commercial and Experimental Alloys

Many of the experimental alloys are compared at a heat treatment of T6 + 18 hr at 325°F because 18 hr was the maximum aging time at 325°F at which strength data were available from the Reynolds program (9). Data for alloy 21 in the T6 + 35 hr at 325°F temper and for another Alcoa alloy, alloy A (11), in a T6 + 2-1/2 hr at 350°F temper are included in Fig. 68.

It was not possible to compare properties of the various materials in the same grain direction. The Alcoa data were taken in the long-transverse direction, the Reynolds data were taken in the longitudinal direction, and the Boeing data were taken in the short-transverse or longitudinal direction, depending on whether the heat treatment was T6 + 18 hr at 325°F or T6 + 35 hr at 325°F. When comparing the data, it should be remembered that short-transverse yield strengths are typically 3 to 5 ksi lower than longitudinal yield strengths.

The data point for X7080-T7 in Fig. 68 represents the average longitudinal yield strength from Ref. 18 for an 8-in.-diam die forging. The data point was plotted at a cooling rate determined for an 8-in.-diam round forging quenched in boiling water, since this is how X7080-T7 die forgings are quenched.

The data point for 7049-T73 in Fig. 68 was obtained by adding 6 ksi to the minimum guaranteed longitudinal yield strength for a 5-in.-diam die forging of that alloy (16). This procedure gives a reasonable value for a typical yield strength. The data point was plotted at a cooling rate determined for a 5-in.-diam round forging quenched in 140°F water, since this is how 7049-T73 die forgings are quenched (41).

The data point for 7175-T736 in Fig. 68 was also obtained by adding 6 ksi to the minimum guaranteed longitudinal yield strength for this alloy (20). The data point for this alloy was plotted at a cooling rate determined for a 3-in.-diam die forging quenched in cold water, since 7175-T736 forgings are cold water quenched. A 3-in. diameter was used because this is the maximum thickness for which the current mechanical properties for 7175-T736 are guaranteed (20).

The data point for Alcoa alloy A in Fig. 68 was plotted at a quench rate based on cold water quenching that assumed the hand forging of alloy A was plate shaped (the forging was 9 in. by 12 in. by 3 in. thick). Alcoa alloy A is a high-copper-content, chromium-free, manganese-bearing 7075-type alloy (11).

Data in Fig. 68 for Alcoa alloys 7375 (a chromium-free version of 7075) + 0.12% Zr, 7375 + 0.34% Mn, and 7075, all in the T6 + 18 hr at 325°F temper, were obtained from Ref. 6.

Data in Fig. 68 for 7075-T6 were taken from Ref. 39.

On a strength basis alone, the data in Fig. 68 indicate that whereas alloy 21 in the T6 + 35 hr at 325°F heat-treatment condition is comparable to recently introduced 7049-T73, both alloys have lower strengths than the current Alcoa and Reynolds developmental alloys. It remains, however, to compare the stress-corrosion resistance of the alloys shown in Fig. 68.

4. STRESS-CORROSION PROPERTIES OF ALLOY 21 AND OTHER COMMERCIAL AND EXPERIMENTAL 7000 SERIES ALLOYS

Although the stress-corrosion threshold for X7080-T7, 7049-T73, 7175-T736, and 7075-T6 are known (Table 20), the relative stress-corrosion resistance of some experimental alloys has not yet been determined. To assess the relative stress-corrosion resistance of the experimental alloys, the following information should be considered.

Stress-corrosion crack growth rate results and smooth-specimen stress-corrosion results for Boeing alloy 21 after a T6 + 20 hr at 325°F treatment (similar to the T6 + 18 hr at 325°F treatment) are given in Figs. 33, 42, 43, 44, and 45. These results indicate that in a T6 + 20 hr at 325°F temper the Boeing alloy would not exhibit adequate stress-corrosion resistance.

Although stress-corrosion properties for Reynolds alloys 2, 3, 8, and 13 have not yet been determined, it might be concluded from the inadequate resistance of alloy 21 after a T6 + 20 hr at 325°F treatment and from the similar compositions of the Boeing and Reynolds alloys (Fig. 1) that the Reynolds alloys also will not have adequate stress-corrosion resistance after a T6 + 18 hr at 325°F treatment.

Some 3.5% NaCl alternate-immersion data for the Alcoa alloys 7075, 7375 + Zr, and 7375 + Mn after a T6 + 16 hr at 325°F treatment are available in Figs. 42 and 43 of Ref. 6. However, because of the excessive pitting that occurred on a number of these specimens, Alcoa states that "final interpretation and evaluation of the composition and aging effects must be delayed until the specimens have been exposed for a sufficient time in the New Kensington atmosphere" (6). All available New Kensington atmosphere data for these three alloys in a T6 + 24 hr at 325°F temper are shown in Table 21. Based on these data, the threshold stresses for the manganese- and zirconium-bearing 7375 are less than 26 ksi. Longer exposure may lower this threshold even further. Thus, with a lesser degree of overaging (T6 + 18 hr at 325°F), 7375 + Mn and 7375 + Zr would not be expected to have adequate stress-corrosion resistance. Table 21 indicates a threshold stress for 7075, which contains chromium, of about 42 ksi; this is as expected, since the T6 + 24 hr at 325°F temper is essentially the T73 treatment and the threshold stress for 7075-T73 is greater than 40 ksi.

That the Alcoa 7375 + Mn and 7375 + Zr alloys exhibit an industrial environment threshold of less than 26 ksi in a T6 + 24 hr at 325°F temper is important to both the Boeing and Reynolds programs. The 7375 alloys contain more copper than either the Boeing or Reynolds alloys, and copper is known to improve stress-corrosion resistance of 7000 series alloys. To achieve an industrial environment threshold of 25 ksi for the Boeing and Reynolds alloys, it appears essential that they be overaged beyond T6 + 24 hr at 325°F. Recall that the final heat treatment for the Boeing alloy 21 was T6 + 35 hr at 325°F.

The excellent mechanical properties of Alcoa alloy A in Fig. 68 demand attention. This alloy is essentially a 7375 + Mn alloy with a high copper content of 2.4%. Alcoa has stated that "accelerated stress-corrosion tests indicate that this material had good resistance to stress-corrosion cracking after it was aged to peak strength at 350°F after a prior T6 treatment (T6 + 2-1/2 hr at 350°F)" (11). Initial tests also indicated that this alloy had much lower quench sensitivity than 7075. The Alcoa work now underway (8, 11, 12, 13, 14, and

Table 20. Stress-Corrosion Threshold Levels for Smooth Short-Transverse Tension Specimens

Alloy and temper	Threshold stress (ksi) 3.5% NaCl alternate immersion	Threshold stress (ksi) Industrial environment	Reference
Alloy 21	> 25	> 25	*
X7080-T7	25	15	6
7175-T736	35	?	20
7049-T73	45	?	40
7075-T73	>47	>47	32
7075-T6	7	14	32
7079-T6	7	6	32

*Estimated values

Table 21. Stress-Corrosion Resistance of Short-Transverse Specimens from 2-Inch-Thick Plate Exposed in New Kensington Atmosphere[a]

Alloy	Heat treatment[b]	Short-transverse yield strength (ksi)	Days to failure after exposure at indicated stress level (ksi)							
			18	26	34	38	42	46	50	54
7075	T6 + 24 hr at 325°F	61.5	OK	OK	OK	OK	OK	489	494	477
7375 + Zr	T6 + 24 hr at 325°F	63.0	OK	447	462	120	364	141	92	92
7375 + Mn	T6 + 24 hr at 325°F	65.3		435	196	214	181	113	102	92

[a]Data taken from Ref. 6, Appendix Tables 31, 35, and 37

[b]Quench rate from solution treatment was 60°F/sec from 750° to 550°F.

15) on the high-copper, chromium-free alloys (Table 1) is a result of these findings on alloy A. Since the vanadium-bearing alloys have been dropped because of intermetallic particle formation (14) and the nickel-bearing alloys may be dropped because of low elongations (15), the Alcoa work is now concentrating on manganese and zirconium additions to their high copper alloys. Data for two of these alloys (alloys 5 and 9) are plotted in Fig. 68. The high mechanical properties for these two alloys are particularly significant. On the basis of what has been said about the benefits of high copper content on stress-corrosion resistance, it appears that although 7375 + Zr could not meet a 25-ksi threshold goal after a treatment of T6 + 18 to 24 hr at 325°F, the higher copper content alloys 5 and 9 possibly could.

Taken collectively, Figs. 53, 54, and 68 and the associated discussion indicate that the mechanical properties of alloy 21 in the recommended heat treatment are comparable to those of the recently introduced Kaiser alloy 7049-T73. Only after completion of stress-corrosion testing of the Alcoa, Reynolds, and Boeing alloys can the relative stress-corrosion resistance of these materials be meaningfully compared with the currently available thick-section Kaiser alloy, 7049-T73.

5. VARIABLES AFFECTING QUENCH SENSITIVITY

Since high copper contents can increase quench sensitivity, it may seem surprising that Alcoa alloy 9 in Fig. 68 shows such high strength, even at quench rates as low as 5°F/sec. However, there are more aspects to quench sensitivity than composition variables. Reynolds (10) has recently found differences in quench sensitivity in the same alloy that depend on whether the material has been hot rolled (600° to 775°F) or warm rolled (400° to 600°F), the warm-rolled material being the most quench sensitive. Reasons for the effect of working temperature on quench sensitivity are as yet unknown.

Another recent study by Holl (3) has indicated that the tramp elements iron and silicon can stimulate quench sensitivity and can magnify the effects produced by minor alloying additions such as manganese and zirconium. Thus, in addition to substantially improving fracture toughness by reducing the concentration of iron and silicon (42,43), quench sensitivity is also reduced. Note the very low iron and silicon contents of nearly all the current thick-section experimental and commercial alloys in Table 1.

6. EFFECTS OF PROCESSING HISTORY

Along with the quench sensitivity differences between warm- and hot-rolled materials, Reynolds has noted a drop in mechanical properties of several ksi in the warm-rolled material that was due to the more recrystallized grain structure. Thus, fabrication practices, which have not even been mentioned as a variable in the present work, can be extremely important in establishing mechanical properties and may have a greater effect on quench sensitivity than composition in some cases. The processing history of the alloy 21 hand and die forgings (Table 22, Appendix I) and the microstructures of these parts (Figs. 49 and 50) show that the material was not highly recrystallized; thus the properties of these parts can be considered typical of properly processed forgings.

7. RATE OF AGING IN CHROMIUM-FREE ALLOYS CONTAINING ZIRCONIUM AND MANGANESE

In view of the long overaging time used for alloy 21 it is interesting that the electrical conductivity values for this alloy are substantially less than the typical values for 7075-T73. Electrical conductivity values for stress-corrosion-resistant tempers of chromium-bearing 7075 usually range from 38% to 42% IACS. These conductivity values for 7075 are usually achieved after fairly short aging times at 325°F (24 to 30 hr). Even after much longer aging times at 325 F, the electrical conductivity of chromium-free, manganese- and zirconium-bearing alloy 21 ranged from 36.6% to 39.8% IACS (Table 6). Based on data from Ref. 6, the lower conductivity of alloy 21 can be attributed to the replacement of chromium by manganese and zirconium. For equivalent zinc, magnesium, and copper contents and for equivalent heat treatments, manganese in particular reduces conductivity (6). These effects have been attributed to a slower aging rate in chromium-free alloys containing manganese or zirconium (6).

8. USE OF DOUBLE CANTILEVER BEAM SPECIMENS FOR STRESS-CORROSION TESTING OF ALUMINUM ALLOYS

The work performed in Phase III of this contract is believed to be the first use of crack growth rate data to aid in the selection of heat treatments in aluminum-alloy development programs. The main advantages of this technique are the speed and simplicity with which the data can be obtained. Stress-corrosion crack growth rates at high K_I values may be compared during the first few weeks after the crack has been initiated. This technique appears to be more discriminating than the smooth-specimen technique in evaluating such alloys as 7079-T6 and 7075-T6 (Fig. 28). Had such data been available several years ago, it is doubtful whether 7079-T6 would have seen such wide usage, and many in-service stress-corrosion problems resulting from its use might have been avoided. Although the DCB technique is less discriminating in comparing tempers that provide more immunity to stress-corrosion, it is apparently still useful, since the selected heat treatment for alloy 21, based on DCB specimen data, was a good choice according to a microscopy study of sectioned tension stress-corrosion specimens (Figs. 42, 43, 44, and 45).

The DCB technique is not intended as a substitute for the smooth-specimen technique but rather should be considered as a complementary technique that is cheaper, simpler, faster, and more quantitative, especially when limited amounts of material are available.

9. INTERPRETATION OF DATA FROM PRECRACKED STRESS-CORROSION SPECIMENS

Since the precracked-specimen approach is fairly new in stress-corrosion testing of aluminum alloys, it seems appropriate to discuss briefly some of the suggested relationships between stress-corrosion data obtained on smooth specimens and those obtained on precracked specimens.

a. K_{Iscc} Approach

One means for merging the two types of data, suggested by Kaufman et al. (44), is illustrated in Fig. 69. In this figure the threshold stress for the stress-corrosion cracking of smooth specimens of 7075-T6510 is used as a cutoff or upper limit for safe stresses derived from the K_{Iscc} values. The generalized equation $K = \sigma \sqrt{\pi a}$, relating stress intensity (K_I), stress (σ), and flaw size (2a), has been used to construct the K_{Iscc} lines in Fig. 69. The implications of this type of plot are that (1) to avoid stress-corrosion cracking, 7075-T6510 should not be stressed at levels above the cutoff even when there are no detectable flaws in the material, and (2) when relatively large flaws are present, 7075-T6510 should not be stressed at levels above that defined by the stress-intensity relationship. The approximate K_{Iscc} value for 7075-T6510 from Ref. 44 used to construct Fig. 69 is much higher than would be expected from the data for 7075-T651 in Fig. 28; subsequently, a second K_{Iscc} line based on a K_{Iscc} value of 5 ksi$\sqrt{\text{in.}}$ has been added to Fig. 69 to show the effect of a lower K_{Iscc} value on this type of plot.

b. Relationship of Smooth and Precracked Specimen Data

Another attempt to relate the data obtained from smooth and precracked specimens is presented in Ref. 26. In this work an interpretation of the smooth-specimen stress-corrosion threshold stress was based on K_I versus stress-corrosion crack growth rate data of the type shown in Fig. 28. For this analysis, the manner in which the stress intensity at the tip of a sharp pit or crack in a tension-type stress-corrosion specimen changes as a function of gross stress and crack depth must be known. To make this calculation, assume that a crack is present in a smooth tension specimen of square cross section. Assume that the crack is present on only one face of this specimen, resulting effectively in a single-edge notched tension specimen. Assume also that a growing stress-corrosion crack in a round tension specimen simulates a single edge notch in a specimen of square cross section. This appears to be a fair assumption, based on the appearance of actual stress-corrosion cracks in round tension specimens (Ref. 26). Then the equation $K_I = \sigma_g \sqrt{\pi a}\ Y$ for a single-edge notched specimen (36) can be used to calculate a family of approximate K_I versus crack depth curves for tension specimens loaded to various gross stress levels. Such a family of curves is shown in Fig. 70 for a square specimen whose cross-sectional area was made equal to that of a 0.25-in.-diam round tension specimen of the type used for stress-corrosion testing purposes in the present work. Thus, the stress levels in Fig. 70 are equivalent to those for a round tension specimen 0.25 in. in diameter.

If an effective K_{Iscc} around 3 ksi$\sqrt{\text{in.}}$ is assumed, then it would be possible, according to Fig. 70, to achieve this K_I level at gross stresses of 20 ksi with a flaw only 0.005 in. deep. For stresses above 40 ksi, a crack depth of only about 0.001 in. is sufficient to achieve a K_I level of 3 ksi$\sqrt{\text{in.}}$ It certainly seems reasonable that such shallow flaws could readily be attained during a stress-corrosion test by simple intergranular attack or pitting. The K_I would increase with crack depth, according to Fig. 70, and stress-corrosion crack growth rate would increase with this increasing K_I level, according to Fig. 28. Failure would occur at a critical stress-intensity value governed by the details of the specimen geometry.

At the lower stresses, say the threshold stress of 7 ksi, a sharp crack nearly 0.036 in. deep is required to attain a K_I level of 3 ksi$\sqrt{\text{in.}}$ For a gross stress below the threshold,

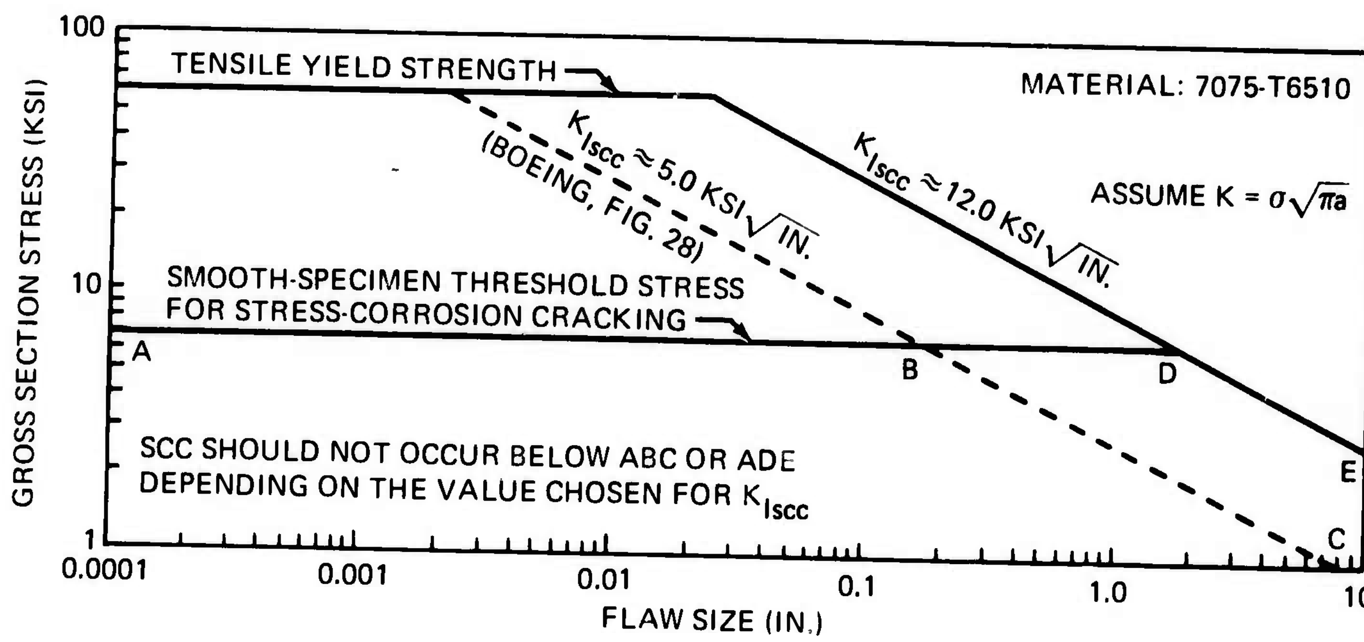


Figure 69. Suggested Method for Combining Stress-Corrosion Data on Smooth and Precracked Specimens for Predicting When Stress-Corrosion Cracking Will Occur (From Ref. 44)

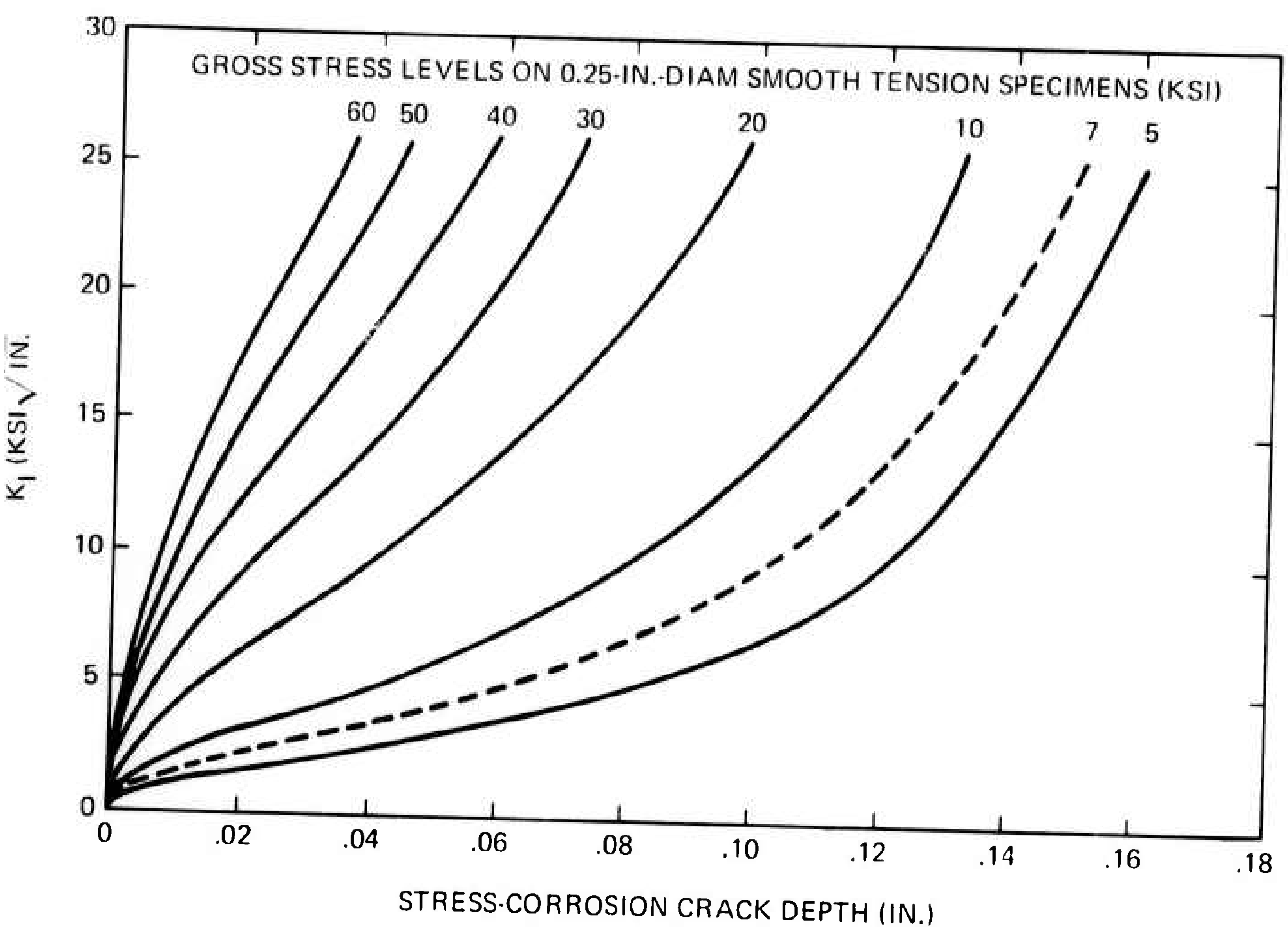


Figure 70. Approximate Stress Intensity Versus Crack Depth Curves for Single-Edge Notched Tension Specimens Loaded to Different Gross Stress Levels (From Ref. 26)

say 5 ksi, a 0.050-in.-deep flaw is required to achieve a K_I level of 3 ksi $\sqrt{in.}$ Such flaw depths are an order of magnitude greater than those required at the higher gross stresses, and it can easily be visualized that at some low stress (the threshold stress) the crack depth required for reaching a K_I level where significant growth rates can be achieved is so deep that, in the normal alternate-immersion test periods for smooth specimens, failure will not occur. In addition, at these lower stresses general corrosion or pitting corrosion can proceed at a rate sufficient to blunt out any sharp, slow-growing intergranular crevices, thus making the effective K_I level even lower than shown in Fig. 70. This combination of events simply prevents the crack from propagating a sufficient distance to cause failure.

10. PROPOSED USE OF DOUBLE CANTILEVER BEAM SPECIMENS FOR TESTING ALUMINUM ALLOYS

Although plots of the type shown in Figs. 69 and 70 may be useful for certain design purposes, it is more probable that data from precracked specimens will find their primary use in rating and comparing alloys and heat treatments. With precracked specimen data and with smooth-specimen backup data, the new and experimental alloys can be more rapidly rated, so that the best alloy for each application can be recommended to the designer. It is proposed here that stress-corrosion crack growth rates at the higher K_I levels be used for this rating procedure for two reasons. First, these data can be obtained rapidly. Second, there is no guarantee that actual K_{Iscc} values exist for many of the high-strength aluminum alloys, since K_I levels below which no growth occurred—true K_{Iscc}—have not been found (Ref. 26).

SECTION VI

CONCLUSIONS

1. Estimated minimum mechanical properties for hand and die forgings of alloy 21 in the T6 + 35 hr at 325°F temper indicate that this material has strength superior to that of 7075-T73 and X7080-T7 and comparable to that of Kaiser's new 7049-T73 thick-section forging alloy. Alloy 21 may have higher strength than 7049-T73 in thicknesses greater than 5 in. (Figs. 53 and 54). However, alloy 21 parts as heat treated for this contract were quenched in 75°F water, whereas similar 7049-T73 and X7080-T7 forgings are quenched in 140°F and 212°F water, respectively. Thus, residual quenching stresses and subsequent distortion during machining would be higher in alloy 21.

2. Neither alloy 21 nor 7049-T73 meet the recent contract goals for a minimum longitudinal yield strength of 63 ksi in an 8-in.-thick forging. Adding 6 ksi to this minimum strength gives a typical strength of 69 ksi. Based on current typical data for the Alcoa and Reynolds alloys in the T6 + 18 hr at 325°F temper, the Alcoa and Reynolds alloys could meet the 69-ksi strength level if quenched at rates greater than 3° to 7°F/sec (Fig. 68). Thus, an 8-in.-diam forging could meet the goal if quenched in water cooler than about 140° to 170°F. Of course it is not yet known whether the stress-corrosion goal for the Alcoa and Reynolds alloys can be met in the T6 + 18 hr at 325°F temper.

3. The stress-corrosion threshold stress for short-transverse smooth specimens of alloy 21 in the T6 + 35 hr at 325°F temper is greater than 25 ksi. The threshold stress in an industrial environment is not yet known and testing in this environment will continue until 1973. It is expected that a threshold stress of at least 25 ksi can be achieved in the industrial environment.

4. Fatigue and fracture toughness properties of alloy 21 are as good as those of 7075-T6, 7075-T73, and 7049-T73.

5. The long aging time at 325°F required for alloy 21 to meet contract stress-corrosion goals is the result of replacing chromium with zirconium and manganese. The composition change lowers the rate of aging in alloy 21, requiring longer aging times to achieve a stress-corrosion-resistant temper.

6. Use of bolt-loaded,double cantilever beam, stress-corrosion specimens in the performance of this contract enabled a heat treatment for alloy 21 to be selected in a much shorter time than would have been possible if only smooth specimens had been used. Based on subsequent metallographic examination of sectioned smooth tension stress-corrosion specimens, the heat treatment selected using DCB data appears to have been a good choice.

SECTION VII

RECOMMENDATIONS FOR FURTHER WORK

1. Continue the surveillance of stress-corrosion specimens in alternate-immersion and industrial-environment exposure tests to more firmly establish the stress-corrosion threshold level for smooth specimens of alloy 21 in the T6 + 35 hr at 325°F temper. Only after this threshold is firmly established and Alcoa and Reynolds contract work is complete can the experimental alloys be rated in relation to 7049-T73. In the meantime, a sample of plate of alloy 21 in the T6 + 35 hr at 325°F temper has been sent to the Naval Air Development Center, Warminster, Pa., for independent evaluation of short-transverse stress-corrosion properties. This laboratory is currently completing an evaluation of 7049-T73.

2. The effects of fabrication variables (temperature, deformation, etc.) on the mechanical properties of high-strength aluminum alloys should be studied.

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APPENDIX I

FORGING FABRICATION AND PHASE I TEST DATA

Table 22. Processing of Wrought Products of Alloy 21

HAND FORGINGS
The hand forgings were processed from two pieces (13 in. in diam by 56.5 in. long) from ingot 21562 and from one piece (13 in. in diam by 26 in. long) from ingot 21563 according to the following schedule:
1. Heat to 750°F and soak
2. Using 10-in. rolling dies in the Sack press, reduce to 10-in. round by length and air cool
3. Cut a 32-in. length of 10-in. round piece from ingot 21562
4. Heat to 750°F
5. Draw on flat dies to 10 in. by 8 in. by length (two pieces)
6. Reheat to 850°F for 2 hr
7. Draw to 10 in. by 6 in. by length (two pieces)
8. Etch in NaOH
The two pieces from ingot 21562 were numbered 251 and 252. The single piece from ingot 21563 was numbered 353.

Table 22–Continued

LANDING GEAR DIE FORGINGS
The material for landing gear die forgings was cut from one piece (10 in. in diam by 66 in. long) from ingot 21562 and from one piece (10 in. in diam by 23 in. long) from ingot 21563 after step 2 in the processing of hand forgings. It was processed according to the following schedule: 1. Heat to 750°F 2. Draw in 6.75-in. rolling dies to 6.75-in. in diam by length 3. Cut two pieces 6.75-in. in diam by 38 in. from piece from ingot 21562 4. Cut one piece 6.75 in. in diam by 38 in. from piece from ingot 21563 5. Heat to 750°F 6. Upset one end of each piece to partially form arms 33 in. long 7. Heat to 820°F 8. Forge in finish dies in 35,000-ton press 9. Etch and grind 10. Heat to 820°F 11. Upset from barrel end to fill parts and form center boss in 35,000-ton press 12. Etch and ship The two pieces from ingot 21562 were numbered 271 and 272. The single piece from ingot 21563 was numbered 373.

Table 22–Concluded

NAVAJO DIE FORGINGS
The material for Navajo die forgings was cut from one piece (6.75 in. in diam by 69 in. long) from ingot 21562 after step 2 in the processing of landing gear die forgings. It was processed according to the following schedule: 1. Cut into three pieces each 6.75-in. in diam by 23 in. long 2. Heat to 750°F 3. Cog end to shape 4. Heat to 750°F 5. Complete open die cogging 6. Etch and grind 7. Heat to 750°F 8. Forge in blocker dies in 18,000-ton press 9. Heat to 820°F 10. Finish forge in 18,000-ton press 11. Etch, grind, and machine flash The three pieces from ingot 21562 were numbered 261, 262, and 263.

Table 23. Hardness Data for Alloy 21 after Various Quenching and Aging Treatments

Quench condition and blank size	Blank no.	Quench rate (°F/sec)	Room temp delay	Hardness[a] after 24 hr at 250°F (R_B)	Hardness[a] fter 24 hr at 250°F + indicated times at 320°F[b] (R_B)								
					8 hr	16 hr	24 hr	30 hr	36 hr	42 hr	46 hr	48 hr	54 hr
212°F Water quench (3- x 2-1/2- x 1-1/4-in. blanks)	1	9	1 hr	89.5	88.4	—	86.5	84.6	86.0	85.3	84.3		
	2		8 hr	89.8	88.3	87.6	86.1	85.1	86.6	84.9	85.2		
	3		5 days	90.1	87.7	86.6	86.1	85.1	86.3	85.5	85.1		
	4		11 days	89.7	88.1	87.0	86.1	84.4	86.2	84.9	83.8		
194°F Water quench (3- x 2-1/2- x 1-1/4-in. blanks)	13	36	1 hr	89.6	87.1	87.3	85.8	84.8	85.6	85.2	84.5		
	14		8 hr	88.9	87.7	—	85.7	85.1	86.2	84.8	84.9		
	15		5 days	89.2	88.2	86.5	84.9	84.2	85.1	85.1	85.2		
	16		11 days	89.9	88.2	87.3	85.7	84.8	85.8	85.5	85.3		
140°F Water quench (3- x 5/8- x 5/8-in. blanks)	58	180	1 hr	93.4	92.4	91.5	89.5	89.2	90.2	89.4		88.8	87.9
	59		1 hr	93.8	92.2	91.4	90.2	89.5	90.0	89.3	—	88.4	88.4
	75		8 hr	93.2	92.3	91.7	90.3	90.0	90.2	89.5	—	88.8	88.1
	76		8 hr	93.9	93.0	91.6	90.8	90.8	90.7	89.4	—	88.9	89.2
	92		5 days	92.8	91.5	90.7	89.8	89.6	89.8	89.2	—	88.1	88.3
	93		5 days	93.1	91.8	91.5	90.1	90.3	89.9	89.7	—	89.2	88.2
	103		11 days	92.9	90.4	90.5	88.3	88.5	90.1	89.6	—	89.2	88.6
	104		11 days	94.0	92.4	91.6	90.6	89.4	90.5	89.4	—	88.6	88.7

[a]Average of three readings

[b]Indicated times are times at temperature. Heatup time in each case was ~ 45 min. After 36 hr at 320°F, aging temperature was increased to 325°F.

Table 24. Electrical Conductivity Data for Alloy 21 after Various Quenching and Aging Treatments

Quench condition and blank size	Blank no.	Quench rate (°F/sec)	Room-temp delay	Conductivity[a] after 24 hr at 250°F (% IACS)	Conductivity[a] after 24 hr at 250°F + indicated times at 320°F[b] (% IACS)								
					8 hr	16 hr	24 hr	30 hr	36 hr	42 hr	46 hr	48 hr	54 hr
212°F Water quench (3 x 2-1/2- x 1-1/4-in. blanks)	1	9	1 hr	31.4	33.7	–	36.0	37.0	37.3	37.8	38.0		
	2		8 hr	31.5	33.7	35.1	36.5	37.0	37.3	37.7	38.0		
	3		5 days	31.4	34.0	35.5	36.5	37.0	37.3	37.8	38.0		
	4		11 days	31.5	34.0	35.5	36.7	37.1	37.3	37.9	38.0		
194°F Water quench (3- x 2-1/2- x 1-1/4-in. blanks)	13	36	1 hr	31.8	34.5	35.6	36.6	37.1	37.3	38.0	38.0		
	14		8 hr	31.5	34.0	–	36.2	37.0	37.3	37.9	38.0		
	15		5 days	31.6	34.5	35.6	36.6	37.3	37.3	37.9	38.0		
	16		11 days	31.5	34.0	35.3	36.3	37.1	37.3	37.8	38.0		
140°F Water quench (3- x 5/8- x 5/8-in. blanks)	58	180	1 hr	30.0	32.9	34.7	35.6	36.1	36.8	37.1	–	37.5	38.0
	59		1 hr	29.9	32.9	34.7	35.6	36.1	36.8	37.1	–	37.5	38.0
	75		8 hr	29.8	32.9	34.7	35.6	36.1	36.8	37.3	–	37.5	38.0
	76		8 hr	29.7	32.9	34.7	35.5	36.1	36.8	37.2	–	37.4	38.0
	92		5 days	29.8	32.9	34.7	35.6	36.3	36.8	37.2	–	37.4	38.0
	93		5 days	29.9	32.9	34.7	35.7	36.1	36.8	37.2	–	37.4	38.0
	103		11 days	29.9	32.9	34.7	35.5	36.0	36.8	37.2	–	37.4	38.0
	104		11 days	30.0	32.9	34.7	35.6	36.0	36.8	37.1	–	37.4	38.0

[a]Average of three readings

[b]Indicated times are times at temperature. Heatup time in each case was ~ 45 min. After 36 hr at 320°F, aging temperature was increased to 325°F.

Table 25. Short-Transverse Mechanical Properties of Alloy 21 after Overaging to an Electrical Conductivity of 38% IACS

Specimen no.	Quench condition and blank size	Quench rate (F/sec)	Room-temp delay	Aging treatment[a]	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 1 in.)	RA (%)
1a			1 hr		70.8	60.8	6.2	6.0
1b			1 hr		70.2	60.7	6.6	8.2
2a	212°F		8 hr		70.0	60.6	4.5	6.7
2b	Water quench	9	8 hr		68.9	60.5	4.3	4.3
3a	(3- x 2-1/2- x		5 days		69.5	60.5	5.5	7.6
3b	1-1/4 blanks)		5 days	24 hr at 250°F	69.6	60.3	5.2	5.2
4a			11 days	+	68.9	60.3	5.7	5.8
4b			11 days	36 hr at 320°F	69.2	60.3	5.1	7.6
13a			1 hr	+	69.2	59.6	4.7	7.4
13b			1 hr	10 hr at 325°F	69.0	59.5	5.8	5.4
14a	194°F		8 hr		68.6	59.7	4.7	7.6
14b	Water quench	36	8 hr		68.9	59.6	5.2	6.6
15a	(3- x 2-1/2- x		5 days		68.2	59.3	5.4	8.6
15b	1-1/4-in. blanks)		5 days		66.9	59.3	3.8	4.5
16a			11 days		70.6	61.5	5.1	5.7
16b			11 days		69.1	60.6	5.5	7.4
58			1 hr		72.9	68.8	8.9	13.7
59			1 hr	24 hr at 250°F	72.6	62.7	8.8	14.4
75	140°F		8 hr	+	73.3	63.1	9.0	17.8
76	Water quench		8 hr	36 hr at 320°F	72.8	62.8	9.9	18.7
92	(3- x 5/8- x	180	5 days	+	73.0	62.8	8.9	16.7
93	5/8-in. blanks)		5 days	18 hr at 325°F	68.2	62.5	–	–
103			11 days		73.0	62.9	10.6	18.4
104			11 days		72.9	63.2	9.9	15.4

[a]All blanks were machined from 3-in.-thick plate.

APPENDIX II

PHASE II MECHANICAL PROPERTY, STRESS-CORROSION, AND CORROSION DATA

Table 26. Phase II Short-Transverse Mechanical Property and Electrical Conductivity Data

Specimen no.	Quench	Approx quenching rate from 750° to 550° F	Heat treatment	Hardness (R_B)	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 1 in.)	RA (%)	Elec Cond (% IACS)
53A	65°F H_2O	500°F/sec	T6	95.6	85.1	73.3	7	13	30.4
53B			T6	95.6	85.3	74.8	5	5	30.4
53C			T6 + 20 hr at 325°F	91.3	78.7	69.3	8	11	36.8
53D			T6 + 20 hr at 325°F	91.3	78.0	69.0	8	11	36.8
54A			T6 + 30 hr at 325°F	89.0	74.7	64.6	7	8	37.8
54B			T6 + 30 hr at 325°F	89.0	75.4	65.6	7	11	37.8
54C			Heat damage	—	—	—	—	—	—
54D			Heat damage	—	—	—	—	—	—
55A			T6 + 40 hr at 325°F	87.4	77.1	67.7	10	21	37.6
55B			T6 + 40 hr at 325°F	87.4	75.7	66.6	6	9	37.6
55C			T6 + 12 hr at 350°F	88.0	73.3	62.8	6	9	37.8
55D			T6 + 12 hr at 350°F	88.0	74.5	63.7	9	18	37.8
5A	140°F H_2O	100°F/sec	T6	92.2	85.4	74.4	4	8	31.0
5C			T6	92.2	85.1	76.9	3	5	31.0
7A			T6 + 10 hr at 325°F	90.9	82.8	75.8	8	11	35.1
7C			T6 + 10 hr at 325°F	90.9	81.7	74.0	5	6	35.1
9A			T6 + 20 hr at 325°F	90.1	80.3	72.7	7	8	36.4
9C			T6 + 20 hr at 325°F	90.1	79.0	70.8	6	12	36.4
11A			T6 + 30 hr at 325°F	88.5	77.0	67.8	7	15	37.1
11C			T6 + 30 hr at 325°F	88.5	76.2	67.4	6	10	37.1
17A			T6 + 40 hr at 325°F	86.3	76.0	66.8	8	12	38.1
17C			T6 + 40 hr at 325°F	86.3	73.7	63.9	6	13	38.1
19A			T6 + 50 hr at 325°F	85.2	73.4	63.3	8	14	38.3
19C			T6 + 50 hr at 325°F	85.2	71.4	59.9	8	12	38.3
21A			T6 + 70 hr at 325°F	84.5	73.0	63.1	8	12	38.4
21C			T6 + 70 hr at 325°F	84.5	70.6	58.8	8	13	38.4
23A			T6 + 12 hr at 350°F	86.1	70.3	65.6	2	6	38.1
23C			T6 + 12 hr at 350°F	86.1	72.7	62.8	7	15	38.1

Table 26.—Continued

Specimen no.	Quench	Approx quenching rate 750° to 550°F	Heat treatment	Hardness (R_B)	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 1 in.)	RA (%)	Elec Cond (% IACS)
25A	140°F H_2O	100°F/sec	T6 + 20 hr at 350°F	84.0	73.0	62.7	7	9	38.2
25C	↓	↓	T6 + 20 hr at 350°F	84.0	71.8	59.6	9	13	38.2
27A	↓	↓	T6 + 25 hr at 350°F	82.5	69.9	57.7	8	17	39.1
27C	↓	↓	T6 + 25 hr at 350°F	82.5	67.8	55.5	7	8	39.1
29A	↓	↓	T6 + 30 hr at 350°F	82.2	69.0	56.7	8	17	39.3
29C	↓	↓	T6 + 30 hr at 350°F	82.2	67.2	54.1	8	13	39.3
31A	212°F H_2O	9°F/sec	T6	90.2	77.0	69.1	2	3	32.2
31C	↓	↓	T6	90.2	74.7	71.0	1	1	32.2
33A	↓	↓	T6 + 10 hr at 325°F	87.8	73.9	68.0	4	3	35.4
33C	↓	↓	T6 + 10 hr at 325°F	87.8	74.2	67.9	6	3	35.4
35A	↓	↓	T6 + 20 hr at 325°F	87.2	73.7	66.2	3	10	36.3
35C	↓	↓	T6 + 20 hr at 325°F	87.2	73.1	66.8	6	3	36.3
37A	↓	↓	T6 + 30 hr at 325°F	85.5	73.2	64.3	5	8	37.4
37C	↓	↓	T6 + 30 hr at 325°F	85.5	72.8	63.7	5	4	37.4
39A	↓	↓	T6 + 40 hr at 325°F	82.5	69.3	58.7	6	9	38.4
39C	↓	↓	T6 + 40 hr at 325°F	82.5	67.6	59.3	4	2	38.4
41A	↓	↓	T6 + 50 hr at 325°F	82.5	69.7	57.0	8	5	38.4
41C	↓	↓	T6 + 50 hr at 325°F	82.5	69.0	59.3	5	6	38.4
43A	↓	↓	T6 + 70 hr at 325°F	79.4	65.2	56.5	4	5	39.3
43C	↓	↓	T6 + 70 hr at 325°F	79.4	65.8	54.6	5	7	39.3
45A	↓	↓	T6 + 12 hr at 350°F	83.7	68.2	58.4	4	7	38.2
45C	↓	↓	T6 + 12 hr at 350°F	83.7	69.3	61.1	4	7	38.2
47A	↓	↓	T6 + 20 hr at 350°F	79.5	66.4	55.0	6	10	39.4
47C	↓	↓	T6 + 20 hr at 350°F	79.5	66.1	54.6	6	8	39.4
49A	↓	↓	T6 + 25 hr at 350°F	80.9	68.2	56.8	6	8	39.1
49C	↓	↓	T6 + 25 hr at 350°F	80.9	67.4	55.5	7	7	39.1
51A	↓	↓	T6 + 30 hr at 350°F	75.7	63.8	51.0	7	11	40.1
51C	↓	↓	T6 + 30 hr at 350°F	75.7	63.9	49.8	8	11	40.1

Table 26—Concluded

Specimen no.	Quench	Approx quenching rate 750° to 550°F	Heat treatment	Hardness (R_B)	F_{tu} (ksi)	F_{ty} (ksi)	Elongation (% in 1 in.)	RA (%)	Elec Cond (% IACS)
56A	Circulating air (room temperature)	1.1°F/sec	T6	78.4	63.7	50.5	5	5	35.4
56B			T6	78.4	63.1	49.9	5	5	35.4
56C			T6 + 20 hr at 325°F	76.7	61.6	50.1	5	2	39.3
56D			T6 + 20 hr at 325°F	76.7	61.2	49.7	5	5	39.3
57A			Heat damage	—	—	—	—	—	—
57B			Heat damage	—	—	—	—	—	—
57C			T6 + 40 hr at 325°F	74.4	59.5	48.5	5	4	40.0
57D			T6 + 40 hr at 325°F	74.4	57.1	48.4	*	3	40.0

*Failed outside gage area

Table 27. Phase II Stress-Corrosion Test Results for Material Quenched in 140°F Water (100°F/Sec) (3.5% NaCl Alternate Immersion)

Heat treatment	Speci-men no.	Sustained stress (ksi)	Days to failure[b]	Residual ultimate stress (ksi)	Residual elong. (% in 1 in.)	Comments
T6 (24 hr at 250°F)	5D		5			
T6 + 10 hr at 325°F	7D		2.5			
T6 + 20 hr at 325°F	9D	50	5.5			
T6 + 30 hr at 325°F	11D		19.5			
T6 + 40 hr at 325°F	17D		42			
T6 + 50 hr at 325°F	19D		70 →	56	6	
T6	6B		12.5			Sectioned
T6 + 10 hr at 325°F	8B		2.5			Sectioned
T6 + 20 hr at 325°F	10B		26.5			Sectioned
T6 + 20 hr at 325°F	9B		24.5			
T6 + 30 hr at 325°F	12B	35	90 →	44.8	0	
T6 + 30 hr at 325°F	11B		54			Sectioned
T6 + 40 hr at 325°F	18B		90 →	44.0	0	
T6 + 40 hr at 325°F	17B		96			Sectioned
T6 + 50 hr at 325°F	20B[a]		90 →			Sectioned
T6 + 20 hr at 325°F	10C		90 →			Sectioned
T6 + 30 hr at 325°F	12C[a]		90 →			
T6 + 30 hr at 325°F	12A	25	90 →			Sectioned
T6 + 40 hr at 325°F	18C		90 →			Sectioned
T6 + 40 hr at 325°F	18A		90 →	60.8	0	
T6 + 12 hr at 350°F	24B		90 →	49.4	0	
T6 + 20 hr at 350°F	26B	35	90 →	41.5	0	
T6 + 25 hr at 350°F	28B		31 →	64.9	4.0	Sectioned

[a]Specimen broke when removed from stress-corrosion fixture.

[b] → Denotes no failure after days indicated.

Table 28. Phase II Stress-Corrosion Test Results for Material Quenched in 212°F Water (9°F/Sec) (3.5% NaCl Alternate Immersion)

Heat treatment	Speci-men no.	Sustained stress (ksi)	Days to failure[a]	Residual ultimate stress (ksi)	Residual elongation (% in 1 in.)	Comments
T6 (24 hr at 250°F)	31D	↑	0.9			
T6 + 10 hr at 325°F	33D		2.5			
T6 + 20 hr at 325°F	35D	50	3			
T6 + 30 hr at 325°F	37D		18.5			
T6 + 40 hr at 325°F	39D		19			
T6 + 50 hr at 325°F	42A	↓	20.5			
T6	32B	↑	0.7			Sectioned
T6 + 10 hr at 325°F	34B		19.5			Sectioned
T6 + 20 hr at 325°F	36B		26.5			Sectioned
T6 + 20 hr at 325°F	35B		26.5			
T6 + 30 hr at 325°F	38B	35	38			Sectioned
T6 + 30 hr at 325°F	37B		72			
T6 + 40 hr at 325°F	40B		35			Sectioned
T6 + 40 hr at 325°F	39B		54			
T6 + 50 hr at 325°F	42B	↓	38			Sectioned
T6 + 20 hr at 325°F	36C	↑	76			Sectioned
T6 + 30 hr at 325°F	38C		60			Sectioned
T6 + 30 hr at 325°F	38A	25	61			
T6 + 40 hr at 325°F	40C		72			
T6 + 40 hr at 325°F	40A	↓	69			Sectioned
T6 + 12 hr at 350°F	46B	↑	38			
T6 + 20 hr at 350°F	48B	35	48			
T6 + 25 hr at 350°F	50B	↓	31 →	51.7	0	

[a] → Denotes no failure after days indicated

Table 29. Residual Strength Data for Unstressed Corrosion Specimens[a]
(3.5% NaCl Alternate Immersion)

Heat treatment	Speci-men no.	Exposure (days)	Residual ultimate stress (ksi)	Residual elongation (% in 1 in.)
140°F water quench				
T6 (24 hr at 250°F)	6D	12.5	63.9	0
T6 + 10 hr at 325°F	8D	2.5	66.1	1.0
T6 + 20 hr at 325°F	10D	26.5	69.2	3.0
T6 + 30 hr at 325°F	12D	90	67.9	4.0
T6 + 40 hr at 325°F	18D	90	70.4	5.0
T6 + 50 hr at 325°F	20D	90	66.2	6.5
T6 + 12 hr at 350°F	24D	90	68.1	4.0
T6 + 20 hr at 350°F	26D	90	65.2	6.5
T6 + 25 hr at 350°F	28D	31	66.5	5.5
212°F water quench				
T6 (24 hr at 250°F)	32D	0.7	75.7	3.0
T6 + 10 hr at 325°F	34D	19.5	64.7	<1.0
T6 + 20 hr at 325°F	36D	26.5	67.1	2.0
T6 + 30 hr at 325°F	38D	38	60.3	3.0
T6 E 40 hr at 325°F	40D	35	62.9	4.0
T6 + 50 hr at 325°F	42D	38	59.2	2.0
T6 + 12 hr at 350°F	46D	38	63.9	4.0
T6 + 20 hr at 350°F	48D	48	55.5	2.0
T6 + 25 hr at 350°F	50D	31	58.7	1.0

[a]An unstressed specimen for each heat treatment and quench rate was removed from test at the time of failure of the corresponding specimen stressed to 35 ksi.

APPENDIX III

TEST SPECIMEN CONFIGURATIONS AND PHASE III MECHANICAL, FRACTURE, AND FATIGUE DATA

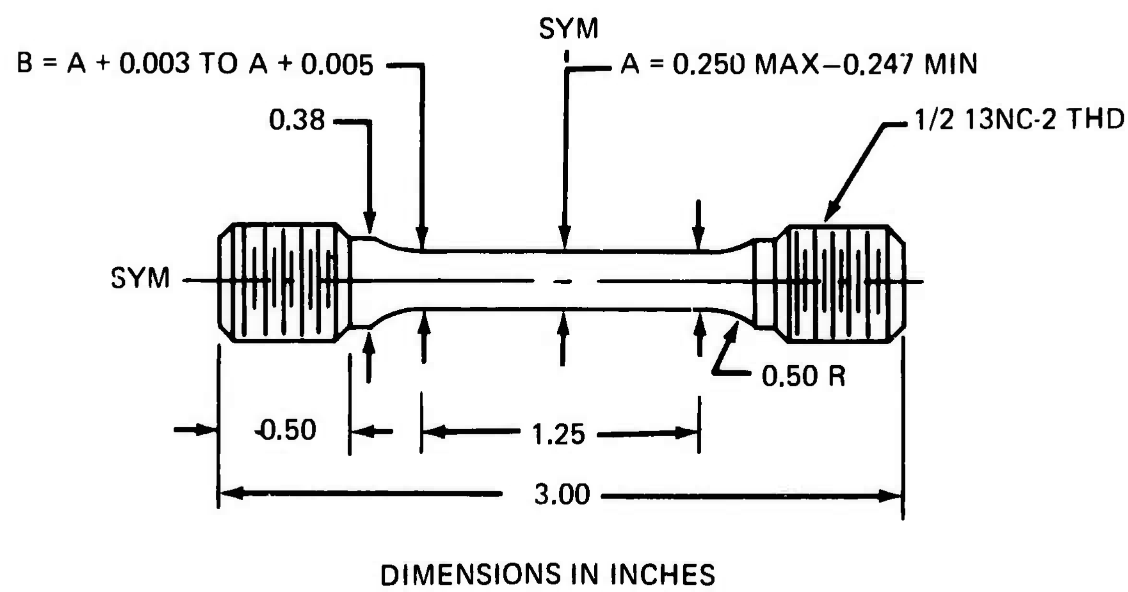


Figure 71. Configuration of Tension and Deadweight Loaded Stress-Corrosion Specimens. Surface Finish for Tension Specimens Was RMS 32 and for Stress-Corrosion Specimens, RMS 16.

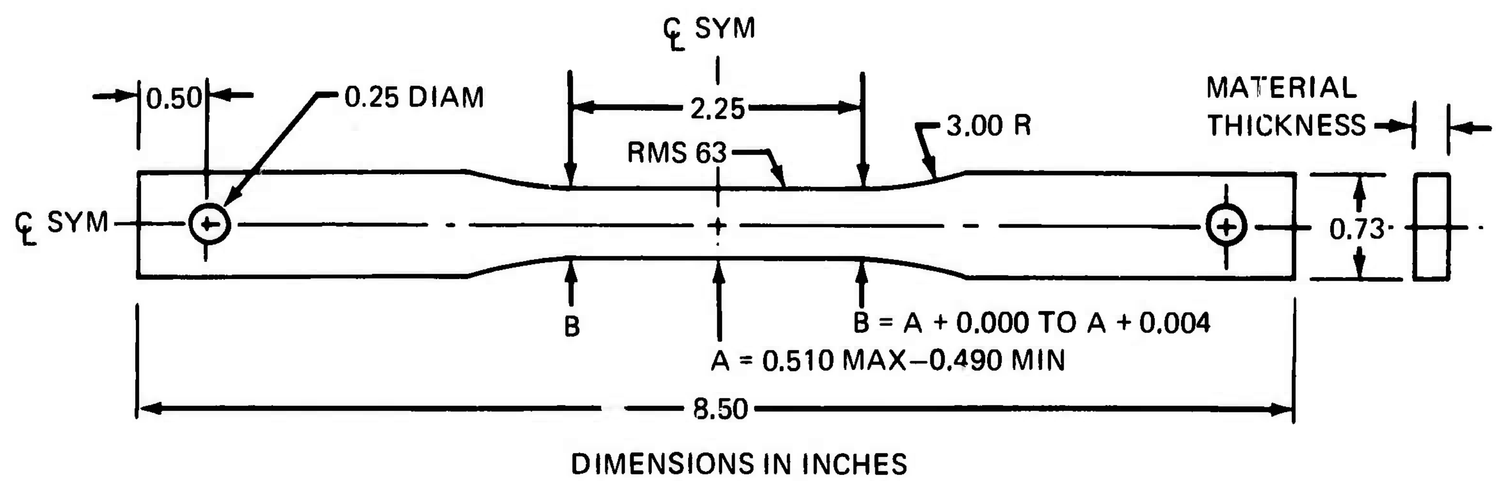


Figure 72. Configuration of Tension Specimens from Angular Extrusions

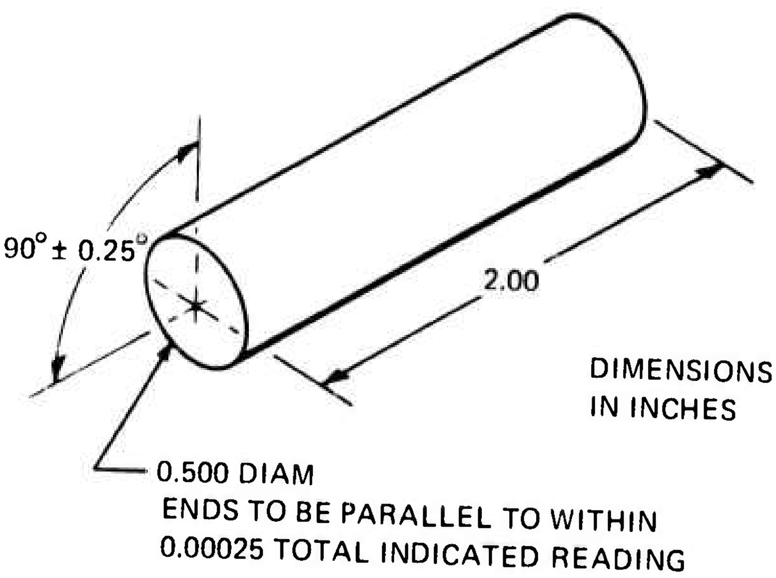


Figure 73. Compression Specimen

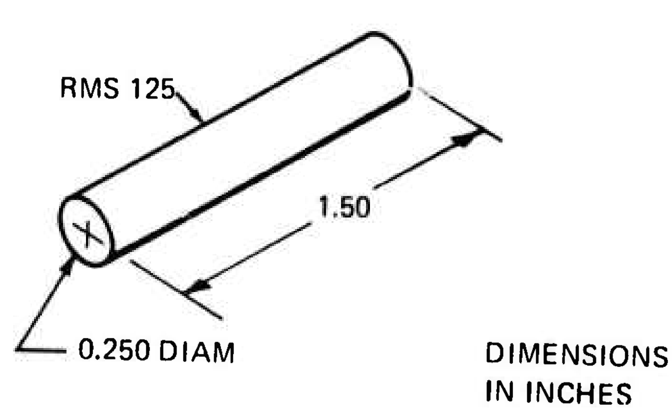


Figure 74. Shear Specimen

D Hole diam	E Edge margin	K Hole diam	M Edge margin	E/D
0.323	0.485	0.359	0.720	1.5
0.323	0.650	0.359	0.720	2.0

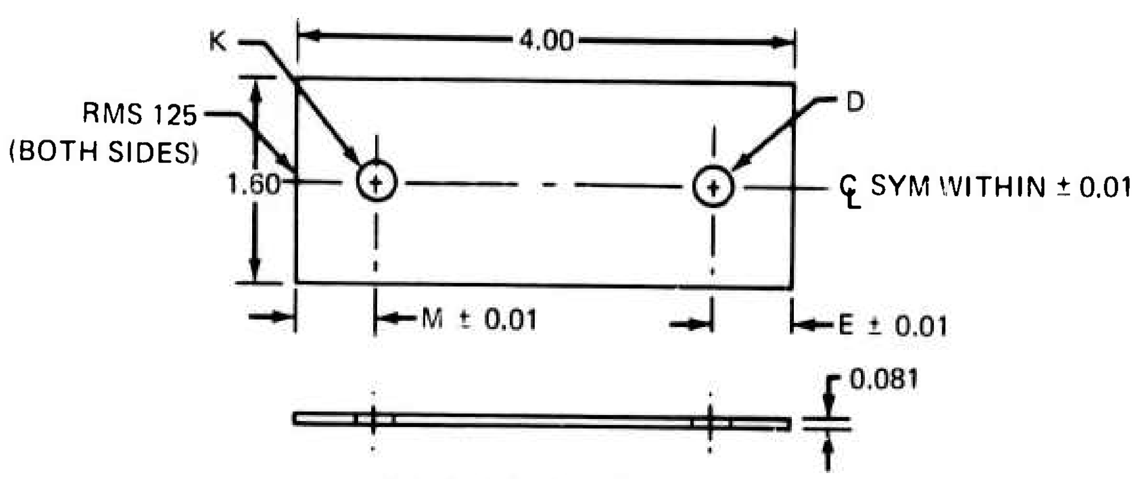
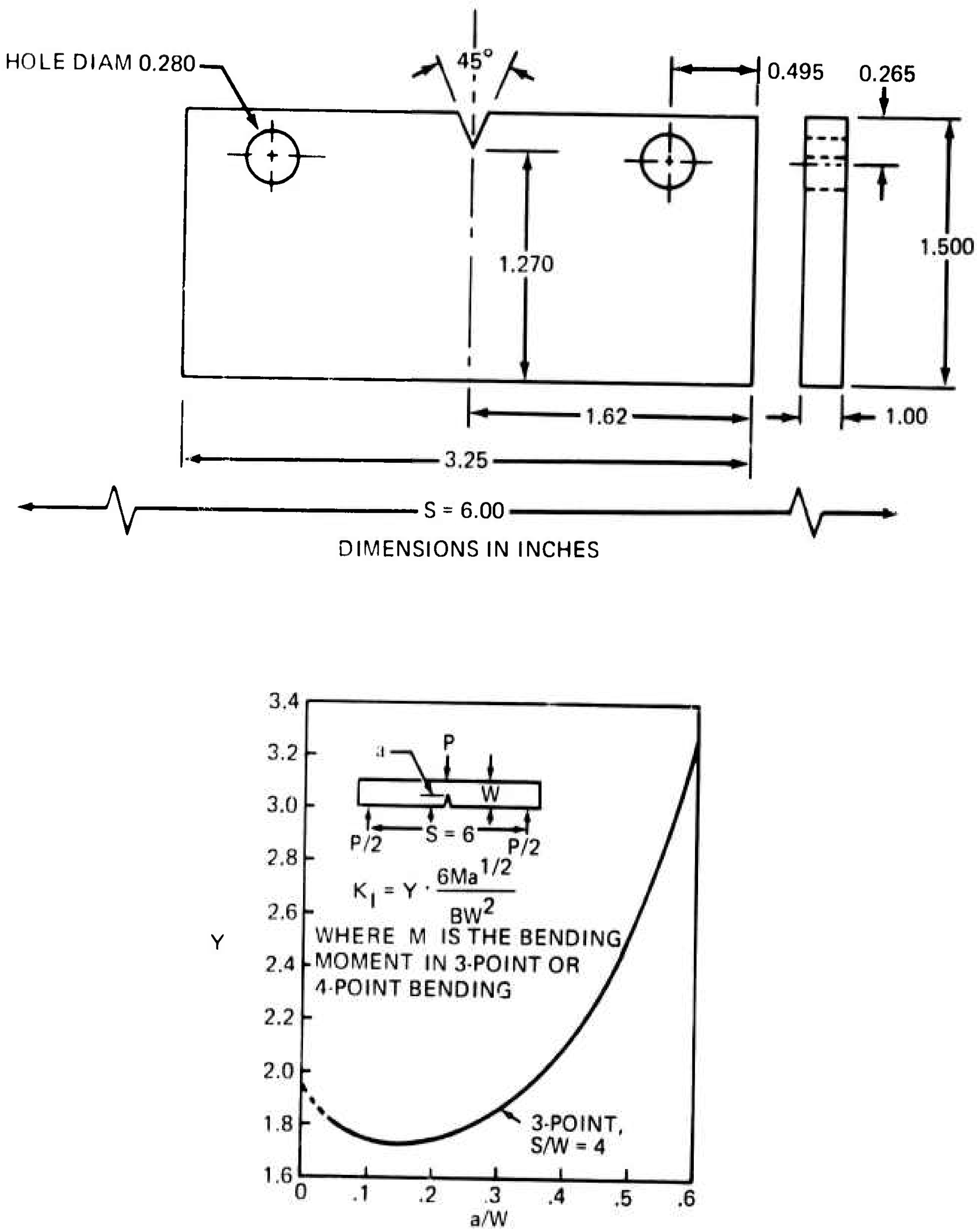


Figure 75. Bearing Specimen



$$Y = K_1BW^2/6Ma^{1/2} = A_0 + A_1(a/W) + A_2(a/W)^2 + A_3(a/W)^3 + A_4(a/W)^4$$

	A_0	A_1	A_2	A_3	A_4
Three-point S/W = 4	+1.93	-3.07	+14.53	-25.11	+25.80

Figure 76. Notched Bend Fracture Toughness Specimen and Associated Formula (Ref. 36)

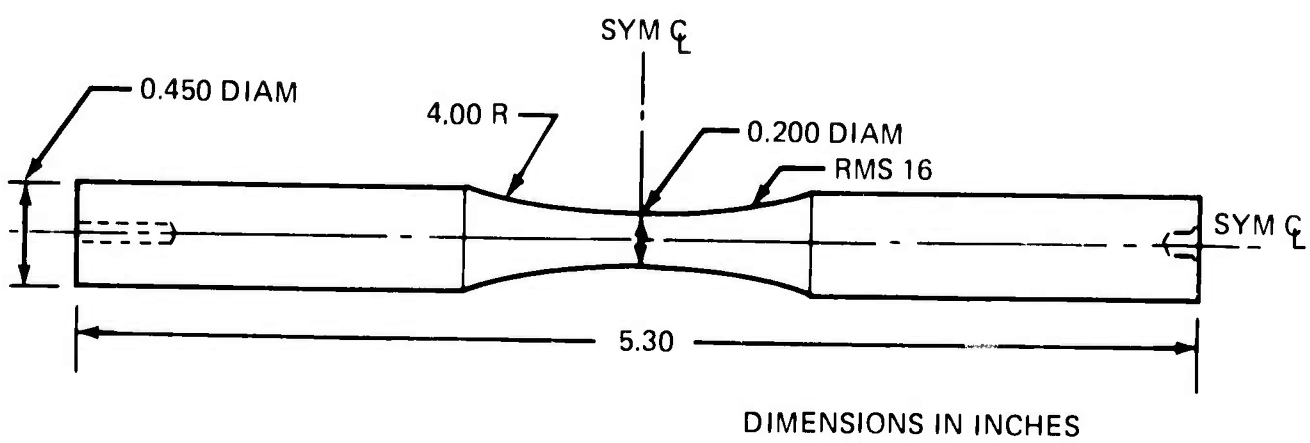


Figure 77. Smooth Axial Fatigue Specimen

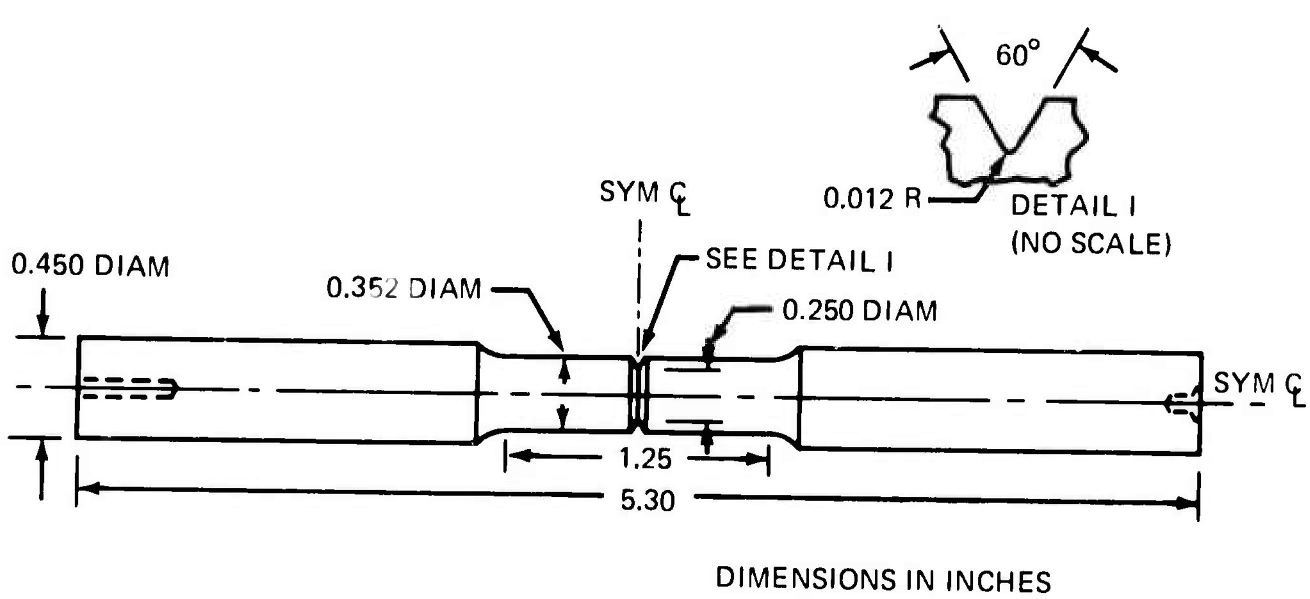


Figure 78. Notched Axial Fatigue Specimen (K_t = 3.0)

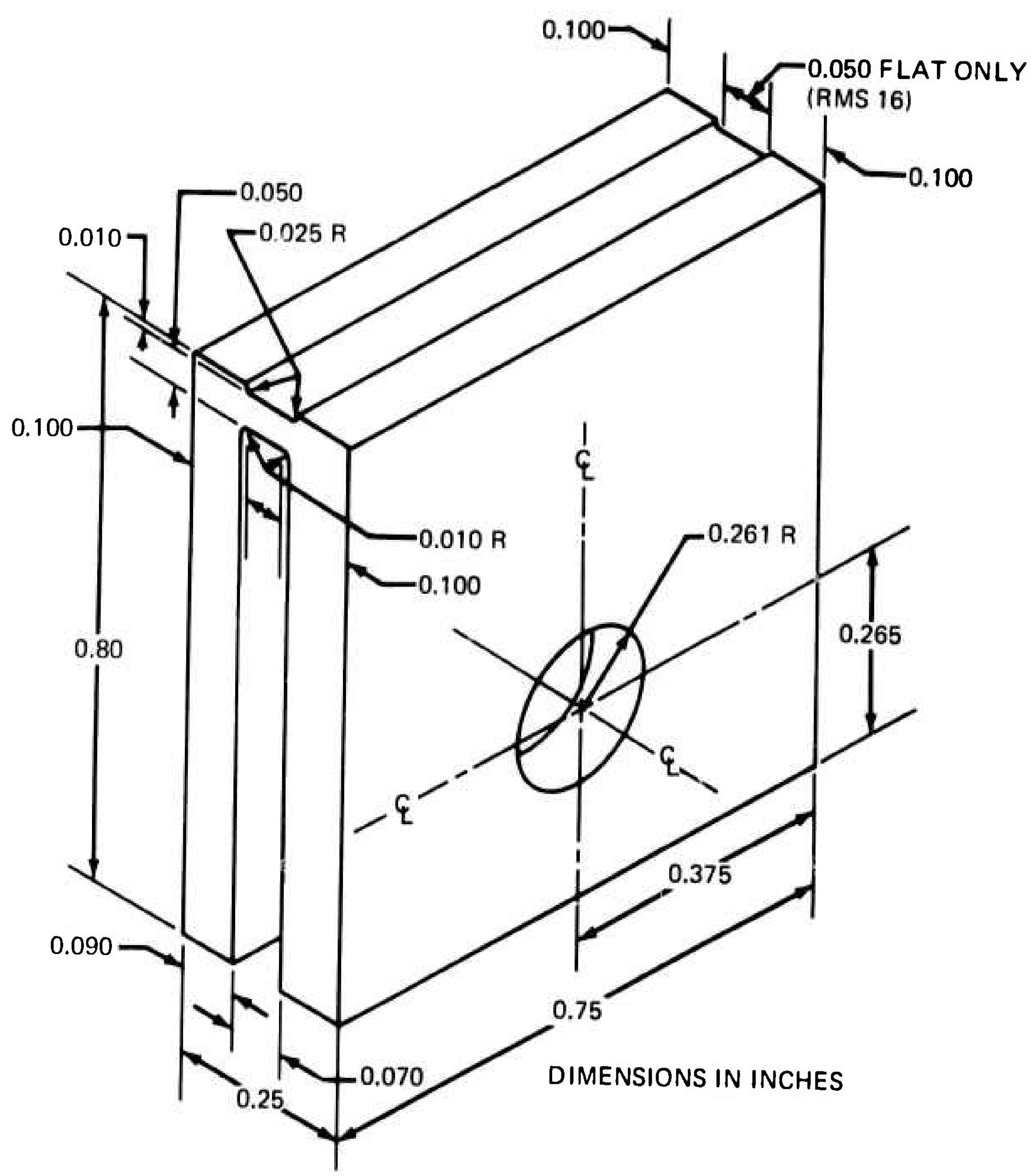


Figure 79. Battelle Tuning-Fork-Type Stress-Corrosion Specimen (Ref. 45)

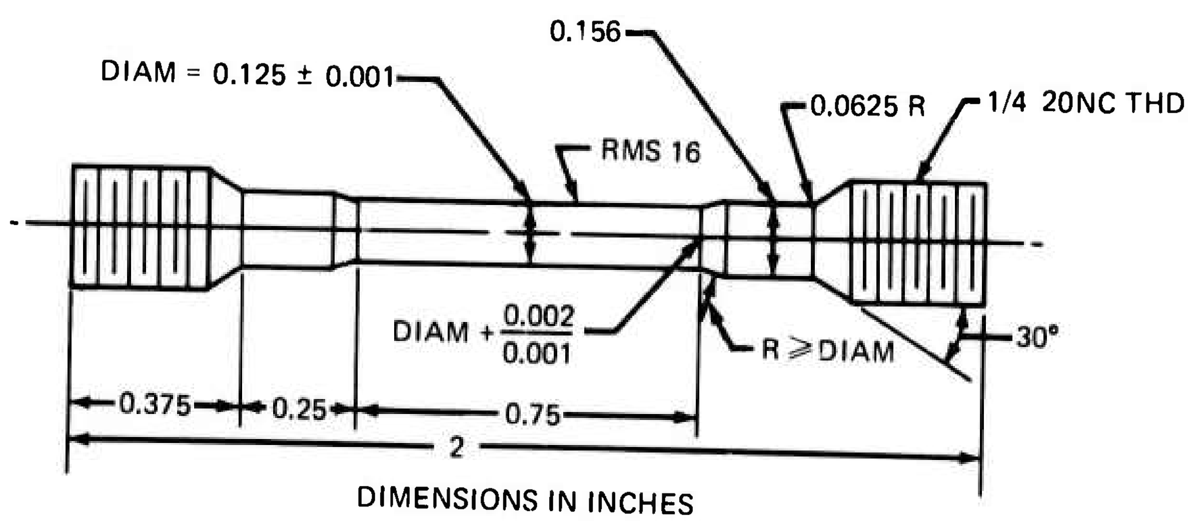


Figure 80. Tension Stress-Corrosion Specimen for Use in Stressing Frame Shown in Figure 65.

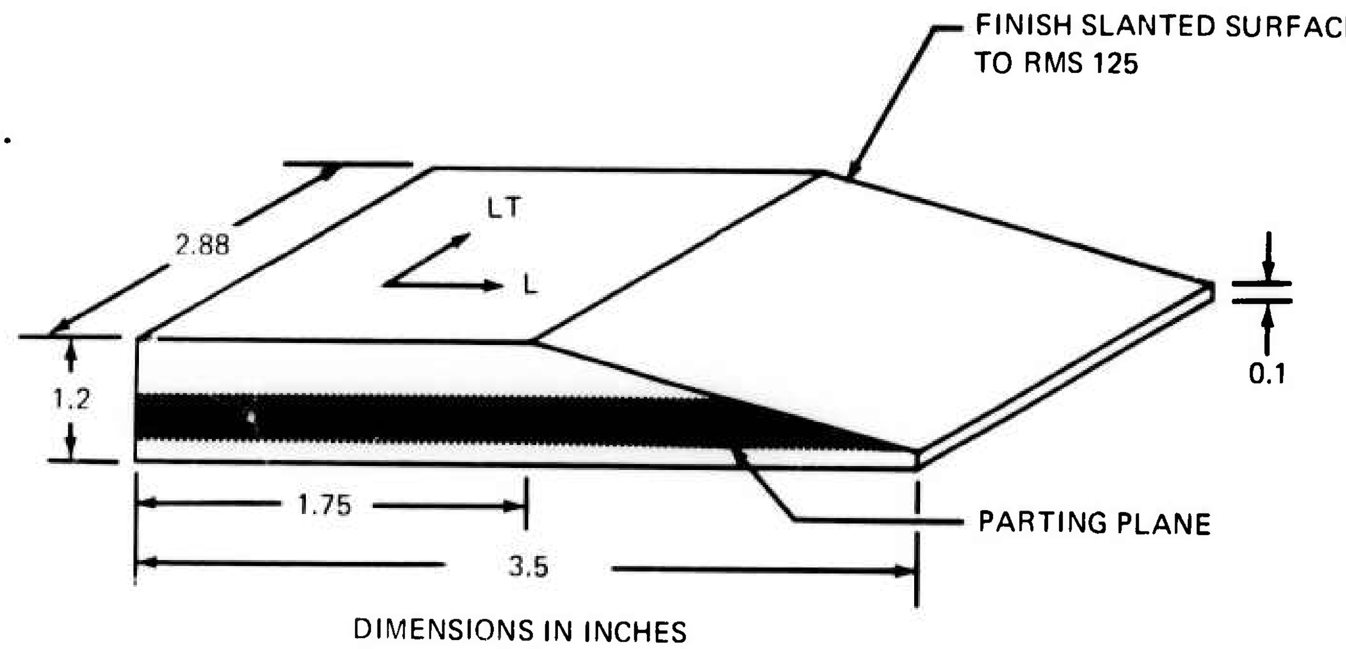


Figure 81. Exfoliation Corrosion Specimen

Table 30. Tension Results for 6.75-In.-Diam by 33-In. Landing Gear Die Forgings

Specimen no.[a]	Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Ultimate strength (ksi)	0.2% Yield strength (ksi)	Elongation (% in 1 in.)	RA (%)
1	21562	271	6.75	6.75	Surface	L	76.0	67.5	14	39.7
2							75.3	67.9	17	40.5
3							75.9	68.0	15	44.6
							75.7	67.8	15	41.6
4					Center		73.9	65.8	12	32.0
5^{1}							74.8	67.1	12	35.2
6^{2}							75.7	67.0	14	37.0
							74.8	66.6	13	34.7
7					Surface	ST	73.8	66.0	7	6.7
8							76.1	66.9	6	5.7
9							74.3	66.2	7	14.1
							74.7	66.4	7	8.8
10^{3}					Center		71.8	62.4	8	8.2
11^{4}							70.5	61.3	9	12.9
12							70.7	63.0	5	5.0
							71.0	62.2	7	8.7
13^{1}	21563[b]	373			Center	L	72.3	64.0	14	36.0
14^{2}							73.7	65.9	14	35.3
							73.0	65.0	14	35.7
15^{3}						ST	68.6	60.4	9	14.2
16^{4}							70.8	61.7	8	13.8
							69.7	61.1	9	14.0

[a]Corresponding superscript numbers denote that specimens were taken from identical locations in forgings.

[b]This ingot contained inclusions.

Table 31. Tension Results for 4- by 6- by 55-In. Navajo Die Forgings

Specimen no.[a]	Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Ultimate strength (ksi)	0.2% Yield strength (ksi)	Elongation (% in 1 in.)	RA (%)
17^1	21562	261	4	4	Surface	L	74.1	65.3	15	41.3
23^1		262					74.8	67.1	15	42.1
							74.5	66.2	15	41.7
18^2		261	4	4	Center		75.9	68.2	13	32.2
24^2		262					75.5	67.6	15	41.2
29^2		263					72.2	64.3	14	44.7
30^2		263					74.0	65.6	16	43.7
							74.4	66.4	15	40.5
19^3		261	0.75	0.75			78.4	72.0	14	44.0
25^3		262					76.3	70.1	15	42.9
							77.4	71.1	15	43.5
20^4		261	4	4		LT	73.2	63.7	10	12.5
26^4		262					71.8	62.7	9	13.8
							72.5	63.2	10	13.2
21^5		261	0.75	0.75			77.4	70.1	14	43.4
27^5		262					77.1	68.9	14	39.5
							77.3	69.5	14	41.5
22^6		261	4	4		ST	71.6	61.9	6	4.4
28^6		262					69.8	61.4	8	11.4
							70.7	61.7	7	7.9

[a]Corresponding superscript numbers denote that specimens were taken from identical locations in forgings.

Table 32. Tension Results for 6- by 10- by 45-In. Hand Forging

Specimen no.[a]	Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Ultimate strength (ksi)	0.2% Yield strength (ksi)	Elongation (% in 1 in.)	RA (%)
31	21562	251	6	6	Center	L	73.1	62.6	13	27.1
32							71.0	62.0	13	23.5
33							74.2	66.0	14	30.6
							72.8	63.5	13	27.1
34						ST	75.5	67.8	8	11.8
35							70.0	59.6	4	4.4
36							68.9	60.0	7	7.5
							71.5	62.5	6	7.9
37		251A		3		L	72.7	63.3	14	34.9
38							73.9	64.8	16	34.2
39							77.7	70.9	13	30.7
							74.8	66.3	14	33.3
40						ST	70.4	62.3	5	6.8
41							72.7	63.5	8	11.0
42							72.8	63.1	17	7.0
							72.0	63.0	10	8.3
43		252		1		L	73.5	64.6	14	40.2
44							71.7	64.1	15	41.8
45							73.7	65.0	16	43.3
							73.0	64.6	15	41.8
46						ST	74.6	63.4	10	16.8
47							71.6	62.3	11	16.5
48							70.7	62.2	8	13.1
							72.3	62.6	10	15.5

Table 33. Tension Results for 6- by 9.5- by 30-In. Hand Forging and 3- by 20- by 43-In. Plate

Specimen no.[a]	Ingot no.	Piece no.	As-worked thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Ultimate strength (ksi)	0.2% Yield strength (ksi)	Elongation (% in 1 in.)	RA (%)
49	Hand forging 21563[a]	353	6	6	Center	L	73.1	63.5	11	24.6
50							71.7	63.0	13	28.6
							72.4	63.3	12	26.6
51						ST	69.4	63.6	3	0.9
52							68.6	63.3	3	2.2
							69.0	63.5	3	1.6
53	Plate 21573	One plate only	3	3	Center	L	76.2	66.6	11	22.7
54							74.7	65.8	11	20.0
							75.5	66.2	11	21.4
55						LT	73.6	65.1	10	14.3
56							70.9	62.6	8	7.9
							72.3	63.9	9	11.1
57						ST	72.0	62.3	6	7.7
58							73.4	64.5	5	7.1
							72.7	63.4	6	7.4

[a]This ingot contained inclusions.

Table 34. Tension Results for Extrusions

Specimen no.[a]	Ingot no.	Piece no.	As-extruded thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Ultimate strength (ksi)	0.2% Yield strength (ksi)	Elongation (% in 1 in.)	RA (%)
59	21560, 0.1 x 0.1 x 72	One piece only	0.1	0.1	Center	L	75.9	67.3	4[a]	20.3
60							76.9	67.7	4[a]	21.6
							76.3	67.5	4	21.0
61	21560, 0.25 x 0.25 x 72	One piece only	0.25	0.25	Center	L	77.7	69.4	5[a]	27.0
62							77.7	69.6	6[a]	28.6
							77.7	69.5	6	27.8
63	21565, 1 x 1 x 72	One piece only	1	1	Center	L	79.5	73.9	12	36.8
64							82.0	76.2	14	43.8
							80.8	75.1	13	40.3
65	21565, 2 x 6 x 72	One piece only	2	2	Center	L	77.6	70.4	14	40.3
66							78.1	71.1	16	42.3
							77.9	70.8	15	41.3
67						ST	75.6	66.3	22[b]	15.1
68							74.9	68.6	10[b]	9.5
							75.3	67.5	16	12.3

[a]Elongation values shown are for 2-in. gage lengths.

[b]Elongation values shown are for 0.5-in. gage lengths.

Table 35. Compression Results for 6.75-In.-Diam by 33-In. Landing Gear and 4- by 6- by 55-In. Navajo Die Forgings

Specimen no.[a]	Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	0.2% Compressive yield strength (ksi)
69	6.75-in. diam x 33-in. landing gear die forging 21562	271	6.75	6.75	Surface	L	72.6
70							72.3
71							72.4
							72.4
75						ST	70.3
76							71.3
77							72.5
							71.4
72					Center	L	69.4
73							71.7
74							71.8
							71.0
78						ST	67.3
79							67.3
80							68.7
							67.8
81[1]	4- x 6- x 55-in. Navajo die forging 21562	261	4	4	Center	L	69.8
83[1]		262					69.1
							69.5
82[2]		261				ST	66.0
84[2]		262					66.8
							66.4

[a]Corresponding superscript numbers denote that specimens were taken from identical locations in forging.

Table 36. Compression Results for 6- by 10- by 45-In. Hand Forging

Specimen no.	Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	0.2% Compressive yield strength (ksi)
85							68.6
86							69.8
87						L	69.8
		251		6	Center		69.4
88							71.7
89						ST	65.9
90							66.1
							67.9
91							67.7
92							71.3
93						L	68.2
	21562	251A	6	3	Center		69.1
94							67.8
95						ST	68.6
96							68.7
							68.4
97							68.3
98							70.3
99						L	68.7
		252		1	Center		69.1
100							70.1
101						ST	69.6
102							68.1
							69.3

Table 37. Compression Results for 3- by 20- by 43-In. Plate and 1- by 1- by 72-In. and 2- by 6- by 72-In. Extrusions

Specimen no.	Ingot no.	Piece no.	As-worked thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	0.2% Compressive yield strength (ksi)
103 104	21573 3- by 20- by 43-in. plate	One piece only	3	3	Center	L	71.0 71.0
							71.0
105 106	21565 1- by 1- by 72-in. extrusion		1	1			77.7 77.9
							77.8
107 108	21565 2- by 6- by 72-in. extrusion		2	2			75.9 75.3
							75.6

Table 38. Shear Results for 6.75-In.-Diam by 33-In. Landing Gear and 4- by 6- by 55-In. Navajo Die Forgings

Specimen no.[a]	Ingot no.	Piece no.	As-forged thickness (in.)	As-heat treated thickness (in.)	Specimen location	Grain direction	Ultimate shear stress (ksi)
109	21562 6.75-in.-diam x 33-in. landing gear die forging	271	6.75	6.75	Surface	L	52.5
110							51.5
							52.0
111					Surface	ST	50.7
112							47.2
							49.0
113[1]		261	4	4	Center	L	48.0
115[1]		262					46.8
							47.4
114[2]	21562 4- x 6- x 55-in. Navajo die forging	261			Center	ST	46.1
116[2]		262					46.6
							46.4

[a]Corresponding superscript numbers denote that specimens were taken from identical locations in forging.

Table 39. Shear Results for 6- by 10- by 45-In. Hand Forging and 3- by 20- by 43-In. Plate

Specimen no.[a]	Ingot no.	Piece no.	As-worked thickness (in.)	As-heat treated thickness (in.)	Specimen location	Grain direction	Ultimate shear stress (ksi)
117	21562 6- x 10- x 45-in. hand forging	251	6	6	Center	L	47.7 48.0
118							47.9
119						ST	44.7 45.0
120							44.9
121		251A		3	Center	L	48.1 49.0
122							48.6
123						ST	47.1 46.6
124							46.9
125		252		1	Center	L	49.9 48.5
126							49.2
127						ST	49.4 48.0
128							48.7
129	21573 3- x 20- x 43-in. plate	One piece only	3	3	Center	L	48.2 48.8
130							48.5
131						ST	46.8 47.5
132							47.2

Table 40. Bearing Results for 6.75-In.-Diam by 33-In. Landing Gear Die Forging

Specimen no.		Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Bearing stresses			
								0.2% YS (ksi)	Ult stress (ksi)	0.2% YS (ksi)	Ult stress (ksi)
E/D=1.5	E/D=2.0							E/D=1.5		E/D=2.0	
133	134	21562	271	6.75	6.75	Surface	L	92.8	113.8	112.2	153.6
135	136							93.2	116.4	109.4	149.6
								93.0	115.1	110.8	151.6
137	138					Surface	ST[a]	117.4	117.4	152.6	158.1
139	140							94.2	113.9	112.0	147.0
								105.8	115.7	132.3	152.6
141	142					Center	L	85.8	102.6	104.0	138.4
143	144							91.0	109.3	107.5	137.1
								88.4	106.0	105.8	137.8

[a]Examination of the specimens revealed that the grain flow in the test section was longitudinal rather than short transverse.

Table 41. Bearing Results for 6- by 10- by 45-In. Hand Forging

Specimen no.		Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Bearing stresses			
								0.2% YS (ksi)	Ult stress (ksi)	0.2% YS (ksi)	Ult stress (ksi)
E/D=1.5	E/D=2.0							E/D=1.5		E/D=2.0	
145	146	21562	251	6	6	Center	L	92.5	109.7	109.4	140.5
147	148							88.2	107.4	106.2	141.4
								90.4	108.6	107.8	141.0
149	150						ST	92.9	113.3	111.0	145.2
151	152							94.8	110.6	114.1	149.0
								93.4	112.0	112.6	147.1
153	154		251A		3	Center	L	93.0	108.3	108.9	143.5
155	156							95.5	117.6	105.2	153.4
								94.3	113.0	107.1	148.5
157	158						ST	92.6	112.3	110.1	145.2
159	160							92.6	113.2	108.1	148.6
								92.6	112.8	109.1	146.9
161	162		252		1	Center	L	89.4	111.5	107.7	148.0
163	164							92.8	114.7	110.4	149.8
								91.1	113.1	109.1	148.9
165	166						ST	89.7	110.2	108.9	143.5
167	168							88.7	108.5	101.7	136.4
								89.2	109.4	105.3	140.0

Table 42. Fracture Toughness Results for 6.75-In.-Diam by 33-In. Landing Gear and 4- by 6- by 55-In. Navajo Die Forgings (Three-Point Loaded Notched Bend Specimen)

Specimen no.[a]		Ingot no.	Piece no.	As-forged thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Plane-strain fracture toughness, K_{Ic} (ksi $\sqrt{\text{in.}}$)
336[1]	6.75-in. diam by 33-in. landing gear die forging	21562	271	6.75	6.75	Center	L	48.5[c,d]
337[2]								
340[1]		21563[b]	373					
341[2]								37.2 38.1
338[3]		21562	271					37.7
339[4]							ST	24.4 26.8
342[3]		21563[b]	373					25.6
343[4]								21.7 21.9
344		21562	261					21.8
345				1.5	1.5	Thin section	L	49.4[d] 46.7[d]
346[5]	4- by 6- by 55-in. Navajo die forging		262	4	4	Thick section	LT	48.1
347[6]			261					30.5 30.8 30.7

[a]Corresponding superscript numbers denote that specimens were taken from identical locations in forging.

[b]This ingot contained small inclusions.

[c]Specimen was not precracked.

[d]$t < 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$

Table 43. Fracture Toughness Results for 6- by 10- by 45-In. Hand Forging, 3- by 20- by 43-In. Plate, and 2- by 6- by 72-In. Extrusion (Three-Point Loaded Notched Bend Specimen)

Specimen no.	Ingot no.	Piece no.	As-worked thickness (in.)	As-heat-treated thickness (in.)	Specimen location	Grain direction	Plane-strain fracture toughness, K_{Ic} (ksi$\sqrt{in.}$)
348						L	42.1[a] 45.7[a]
349							43.9
350		252		6	Center	ST	29.5 25.0
351							27.3
352	21562 6- by 10- by 45-in. hand forging	251A	6	3	Center	L	52.0[a] 42.9[a]
353							47.5
354		252		1		L	51.2[a] 50.5[a]
355							50.9
356						L	48.6[a] 47.8[a]
357							48.2
358	21573 3- by 2- by 43-in. plate		3	3	Center	LT	33.1 31.5
359							32.3
360						ST	28.5 29.3
361							28.9
362	21565 2- by 6- by 72-in. extrusion		2	2	Center	L	59.4[a] 59.7[a]
363							59.6

[a] $t < 2.5 \left(\frac{K_{Ic}}{\sigma_{ys}}\right)^2$

Table 44. Smooth Axial (Tension-Tension) Fatigue Results for 6.75-In.-Diam Landing Gear Die Forging

Specimen no.	Ingot no.	Thickness (in.)		Grain direction	Maximum stress (ksi)	Stress ratio, R	Number of cycles to failure[a]
		As-fabricated	As-heat-treated				
170	21562	6.75	6.75	L	50	0.1	2,065,000 NF
172							3,051,000 NF
173							2,508,000
169					40		2,345,000 NF
171							1,914,000
174							2,495,000
176				ST	50		21,000
178							46,000
179							62,000
175					40		77,000
177							1,784,000
180							279,000

[a]NF denotes no failure.

Table 45. Notched Axial (Tension-Tension) Fatigue Results for 6.75-In.-Diam Landing Gear Die Forging

Specimen no.[b]	Ingot no.	Thickness (in.)		Grain direction	Maximum stress (ksi)	Stress ratio, R	Theoretical stress concentration factor, K_t	Number of cycles to failure[a]
		As-fabricated	As-heat-treated					
181	21562	6.75	6.75	L	25	0.1	3.0	70,000
184								42,000
186								48,000
182					20			53,000
185								151,000
187								178,000
183					10			1,334,000 NF
189								1,891,000 NF
188								1,000,000 NF
192[1]				ST	20			61,000
193[2]								86,000
194								113,000
191[3]					15			14,589,000 NF
197[4]								252,000
195								619,000
190					10			1,064,000 NF
198								2,528,000 NF
196								887,000
201[1]	21563[c]				20			63,000
202[2]								61,000
200[3]					15			217,000
203[4]								131,000
199					10			1,181,000 NF
204								6,210,000 NF

[a]NF denotes no failure.
[b]Corresponding superscript numbers denote that specimens were taken from identical locations in forgings.
[c]This ingot contained small inclusions.

Table 46. Notched Axial (Tension-Tension) Fatigue Results for 6- by 10- by 45-In. Hand Forging

Specimen no.	Ingot no.	Thickness (in.) As-fabricated	Thickness (in.) As-heat-treated	Grain direction	Maximum stress (ksi)	Stress ratio, R	Theoretical stress concentration factor, K_t	Number of cycles to failure[a]
205								49,000
211					25			57,000
212								70,000
208								103,000
213				L	20			78,000
206								96,000
207								1,062,000 NF
209			6		10			1,323,000 NF
210								1,000,000 NF
214								71,000
217					20			39,000
218								51,000
221								1,386,000
215				ST	15			4,183,000 NF
220								2,392,000 NF
216								314,000
219					10			1,026,000 NF
222	21562	6				0.1	3.0	653,000
225								50,000
230					25			63,000
229								56,000
226								63,000
231				L	20			71,000
228								255,000
223								663,000
227					10			1,702,000 NF
224			1					805,000
240								76,000
236					20			106,000
238								89,000
237								1,009,000 NF
239				ST	15			351,000
234								193,000
232								6,734,000 NF
233					10			999,000 NF
235								1,070,000 NF

[a]NF denotes no failure.

Table 47. Notched Axial (Tension-Tension) Fatigue Results for 2- by 6- by 72-In. Extrusion

Specimen no.	Ingot no.	Thickness (in.)		Grain direction	Maximum stress (ksi)	Stress ratio, R	Theoretical stress concentration factor, K_t	Number of cycles to failure
		As-fabricated	As-heat-treated					
241	21565	2	2	L	25	0.1	3.0	66,000
244								68,000
243								58,000
242					20			80,000
245								68,000
246								57,000

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13. ABSTRACT

Several heats of a Boeing-recommended alloy (alloy 21) were cast by Reynolds and fabricated by Reynolds and Wyman-Gordon into die forgings, hand forgings, plate, and extrusions. All the wrought products were forwarded to Boeing for heat-treatment and evaluation of mechanical, fracture, fatigue, and stress corrosion properties. The degree of overaging required to achieve a 25-ksi smooth-specimen threshold stress was determined using stress-corrosion crack growth rate data from precracked double cantilever beam specimens, and a T6+35 hr at 325 F treatment was finally selected. The mechanical properties of alloy 21 are comparable to those of 7049-T73. The fracture toughness is as good as or better than that of other high strength alloys. The smooth-specimen short-transverse stress-corrosion threshold appears to be greater than 25-ksi. The smooth and notched axial (tension-tension) fatigue properties are comparable to those of 7075-T6 and 7075-T73.

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High Strength Alloys						
Stress Corrosion Resistance						
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